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# LANGLEY ABBEY, LANGLEY WITH HARDLEY, NORFOLK
# TREE-RING ANALYSIS OF TIMBERS

## SCIENTIFIC DATING REPORT

Alison Arnold and Robert Howard

INTERVENTION
AND ANALYSIS

ENGLISH HERITAGE

Research Report Series 25-2014

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Alison Arnold and Robert Howard

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SUMMARY
Analysis undertaken on samples from the former west cloister and former stables of Langley Abbey resulted in the construction of two site sequences. Site sequence LNGLSQ01 contains three samples and spans the period AD 1313–1424 and LNGLSQ02 contains 26 samples and spans the period AD 1436–1611.

Interpretation indicates that the roof of the former west cloister contains timber felled in AD 1605–30. The south end of the former stables has a truss constructed from timber felled in AD 1433–58, whilst the rest of the dated timber from this building is late-sixteenth and early seventeenth century in date.

CONTRIBUTORS
Alison Arnold and Robert Howard

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## INTRODUCTION

The Grade 1 listed remains of the Premonstratensian Abbey of Langley is situated in the parish Langley with Hardley some 16km south-east of Norwich (Figs 1–3). Founded in AD 1195, extant remains and excavations have shown the abbey to have consisted of a cruciform aisled church with a tower at the west end, a presbytery flanked by chapels, and an additional chapel north of the north transept with the claustral buildings arranged to the south. These included the sacristy, chapter house, parlour, dorter, and its sub-vault and warming house in the east range, the frater in the south range, and a cellarium in the west range (Fig 4). The monastery was dissolved in AD 1536 (www.pastscape.org).

Extant remains of the abbey buildings include two barns that were formerly the stable block (west barn) and the west range of the cloister of the abbey (east barn).

### Former west range of cloister

This Grade 1 building is thought to date from the thirteenth century but has experienced substantial remodelling since this time. Its structure comprises limestone, brick, and flint with red brick, and limestone dressings (Fig 5). The main block was originally of two-and-a-half storeys with vaulting above the ground floor. It has a steeply-pitched, thatched roof over the south end, with a later, shallower-pitched, pantiled roof to the north; the north gable retains the line of the earlier roof. The roof comprises two tiers of butt purlins, tiebeams, and collars to principal rafters and appears to be a mixture of modern and historic timbers. Additionally, trusses 5, 6, and 8 retain wall-posts (either both or just to one side) and there are arch-braces to the west side of trusses 5 and 6 (Fig 6). This building is part of the Scheduled Ancient Monument.

### Former stable block

This Grade II* listed building on the Heritage at Risk register, has a red-brick ground floor with jettied timber-framed upper storey, beneath a steeply pitched, thatched roof (Fig 7). The roof is of a clasped purlin type, with curved wind bracing and surviving arch-braces to the two central tiebeams (Fig 8). Trusses 6 and 7 are immediately adjacent to each other suggesting they may have originally belonged to two separate buildings (Fig 9). The exposed first-floor frame consists of closely-set joists and bridging beams supported by timber posts (Fig 10). The building is currently thought to be sixteenth century with a rebuilt south gable in brick dating to the twentieth century.

## SAMPLING

A dendrochronological survey was requested by John Etté (English Heritage, Heritage at Risk Principal Adviser) and coordinated by Will Fletcher (English Heritage, Inspector of Ancient Monuments) to ascertain whether the former stable block (the west barn) dates to pre- or post-dissolution in the early–mid sixteenth century and whether a similar date can be determined for the roof of the west range of the cloister. Additionally, dendrochronological dating evidence from the former stable block will contribute to the strategy for repair.

A total of 44 timbers from the former west range of the cloister and stable block was sampled by coring. Each sample was given the code LNG-L and numbered 1–44. Samples LNG-L01–15 were taken from the former west cloister range roof and LNG-L16–44 from the former stable block. The locations of all samples were noted at the time of sampling and are shown on Figures 11–21. Further details relating to the samples can be found in Table 1.

## ANALYSIS AND RESULTS

Four samples, one from the former western cloister, two from the former stable block roof, and one from the ground-floor ceiling, had too few rings for secure dating and so were rejected prior to measurement. The remaining 40 samples were prepared by sanding and polishing and their growth ring-widths measured; the data of these measurements are given at the end of the report. All samples were then compared with each other by the Litton/Zainodin grouping programme (see Appendix).

Firstly, three samples, all from truss 7 of the former stable block roof, matched each other and were combined at the relevant offset positions to form LNGLSQ01, a site sequence of 112 rings (Fig 22). This site sequence was compared against a series of relevant reference chronologies for oak where it was found to match consistently and securely at a first-ring date of AD 1313 and a last-measured ring date of AD 1424 The evidence for this dating is given in Table 2.

Twenty-six samples matched each other and were combined at the relevant offset positions to form LNGLSQ02, a site sequence of 176 rings (Fig 23). This site sequence was compared against a series of relevant reference chronologies for oak where it was found to span the period AD 1436–1611. The evidence for this dating is given in Table 3.

Attempts to date the remaining 11 ungrouped samples by individually comparing them against the reference chronologies were unsuccessful and all remain undated.

## INTERPRETATION

Felling date ranges have been calculated using the estimate that mature oak trees in this region have 15–40 sapwood rings.

## Former west range of cloister

Twelve of the samples taken from this building have been successfully dated within site sequence LNGLSQ02. All 12 samples have the heartwood/sapwood boundary ring date, which in all cases is broadly contemporary ranging from AD 1577 to AD 1597 and suggestive of a single felling (Fig 24). The average of this is AD 1590, allowing an estimated felling date to be calculated for the 12 timbers represented to within the range AD 1605–30.

## Former stable block

Seventeen samples taken from the roof and floor frame of this building have been successfully dated (Fig 24), three within site sequence LNGLSQ01 and the remainder within LNGLSQ02.

### Roof

Three of the roof samples, all from truss 7, are substantially earlier than the rest of the dated timber. Two of these (LNG-L42 and LNG-L44) have similar heartwood/sapwood boundary ring dates, the average of which is AD 1418, allowing an estimated felling date range to be calculated for the two timbers represented to within the range AD 1433–58. The third sample (LNG-L41) does not have the heartwood/sapwood boundary ring and so an estimated felling date cannot be calculated for it, except that with a last-measured heartwood ring date of AD 1381 this would be after AD 1396. However, this sample matches LNG-L42 at $t$=10.2 which is of a level which might suggest both timbers were cut from the same tree, meaning this timber would also have been felled in AD 1433–58.

Of the other nine dated roof samples, sample LNG-L17, taken from the tiebeam of truss 2, has complete sapwood and the last-measured ring date of AD 1611, the felling date of the timber represented. Seven further samples have the heartwood/sapwood boundary ring; the date of which varies from AD 1551 (LNG-L16) to AD 1577 (LNG-L20). Given that sample LNG-L17 has the heartwood/sapwood boundary ring date of AD 1586 this would give a difference in heartwood/sapwood boundary of 35 years, somewhat greater than would be expected for a group of coeval timbers.

The sample with the earliest heartwood/sapwood boundary ring date is LNG-L16, taken from the tiebeam of truss 1. This is AD 1551 which allows an estimated felling date to be calculated for the timber represented to within the range AD 1566–91.

There are five samples (taken from three studs and two tiebeams) with very similar heartwood/sapwood boundary ring dates (LNG-G21, LNG-G22, LNG-G27, LNG-G28, and LNG-G30); the difference between these heartwood/sapwood boundary ring dates is only six years, entirely consistent with contemporary felling. The average heartwood/sapwood boundary ring dates for these five samples is AD 1564, giving an estimated felling date range for the timbers represented of AD 1579–1604.

Sample LNG-L20 has a slightly later heartwood/sapwood boundary ring date of AD 1577, allowing an estimated felling date to be calculated for the timber represented to within the range AD 1592–1617, consistent with this timber having been felled in AD 1611.

The final dated sample, LNG-L29, does not have heartwood/sapwood boundary but with a last-measured heartwood ring date of AD 1556, this timber would be estimated to have a *terminus post quem* felling of AD 1571. Furthermore, sample LNG-L29 matches samples LNG-L27, LNG-L28, and LNG-L30 with *t*-values in excess of 10, with all four stud posts likely to have been cut from the same tree and therefore, felled at the same time (AD 1579–1604).

### Floor frame

Two of the samples taken from the floor frame have complete sapwood and the last-measured ring date of AD 1611, the felling date of the timber represented. Of the other three dated floor frame samples, one (LNG-L34) has the heartwood/sapwood boundary ring date of AD 1577, allowing an estimated felling date to be calculated for the timber represented within the range AD 1592–1617, consistent with this timber also having been felled in AD 1611. The two samples without the heartwood/sapwood boundary have last-measured ring dates of AD 1541 (LNG-L33) and AD 1592 (LNG-L35), giving *terminus post quem* felling dates of AD 1556 and AD 1607, respectively. These two samples can be seen to match other floor frame samples at values of $t$=8.0 and above (LNG-L33 matches LNG-L34 at $t$=8.0 and LNG-L35 matches LNG-L32 at $t$=8.3) perhaps lending some evidence to suggest that these two timbers were also felled in AD 1611. A caveat to this would be that, given the variation in felling date ranges for the timber utilised in the roof above, one cannot be certain that all of these floor timbers were felled at precisely the same time.

## DISCUSSION

Dendrochronological research has successfully dated beams from both the former west range of the cloister and stable block, identifying timbers of pre- and post-dissolution date.

The earliest timbers have been identified within truss 7 of the former stable block, where two posts and a principal rafter have been dated to AD 1433–58. As mentioned in the introduction, this truss is located immediately adjacent to truss 6, which might suggest two separate building phases. Indeed, timber dated from the roof over the rest of this building has been found to be substantially later. The tiebeam of truss 1 has been dated to AD 1566–91, four studs and the tiebeams of trusses 4 and 5 dated to AD 1579–1604, the tiebeam of truss 2 to AD 1611 and collar of truss 3 dated to AD 1592–1617. The floor frame of the former stable block has also been found to contain timber dating to AD 1611.

It had been suggested that most of the roof timber in the former stable block was original (Donal MacGarry pers comm), and it is unclear how the slightly different dates that have been gained for these should be interpreted. The central bays (between trusses 3–6) were thought to be the earliest phase and it is from these that the six samples dated to AD 1579–1604 can be found. The tiebeam of truss 1 has a slightly earlier but overlapping felling date range of AD 1566–91, making it possible that all seven timbers were felled in AD 1579–91. The timbers dated to AD 1611 (with felling date ranges consistent with an AD 1611 felling) are from roof trusses 2 and 3, and from the floor frame below trusses 1–3, could relate to modification in this part of the building. Alternatively it may be that construction simply occurred in or soon after AD1611 utilising a degree of stockpiled or reused material, although no obvious signs of reuse were noted during sampling.

The dendrochronology appears to show the incorporation of a truss belonging to a mid fifteenth-century building into a later structure. Interestingly, it can be seen that the tiebeam of truss 7 is very similar in appearance to that of truss 3 with a distinctive 'bend' in it (Figs 8 and 25). The tiebeam of truss 3 was deemed unsuitable and not sampled whilst that of truss 7 has 47 rings only and is undated. Although conjecture, it may be that these two tiebeams are cut from the same tree suggesting the inclusion of at least one salvaged fifteenth-century timber in the main body of the barn (date by association with the other timber elements in this truss). Furthermore, this tiebeam appears to have an empty mortice for a brace with no matching mortice on the wall-post suggesting that either it is reused or the wall-post is a replacement.

A number of timber elements from the former west range of the cloister are now known to have been felled in AD 1605–30. It can be seen that this felling date range encompasses the AD 1611 date gained for a number of the beams from the former stables. Additionally, there is evidence for possible same tree matches between the two areas with sample LNG-L17, taken from the tiebeam of truss 2 in the former stables matching common rafters (LNG-L13 and LNG-L15) from the former west cloister particularly well ($t$=10.2 and 9.9).

The apparently contemporary nature of the surviving timber from the former cloister and stable block poses the question as to whether the structures are indeed of the same early seventeenth-century date or whether one utilises salvaged material from the other, although if the latter is the case this reuse is not obvious. These buildings would undoubtedly benefit from further study from a buildings specialist.

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# TABLES

*Table 1: Details of samples from Langley Abbey, Langley with Hardley, Norfolk*

| Sample number | Sample location | Total rings* | Sapwood rings** | First measured ring date (AD) | Last heartwood ring date (AD) | Last measured ring date (AD) |
|---|---|---|---|---|---|---|
| Former west range of cloister | | | | | | |
| LNG-L01 | East wallpost, truss 5 | NM | -- | ---- | ---- | ---- |
| LNG-L02 | West wallpost, truss 5 | 94 | 04 | 1506 | 1595 | 1599 |
| LNG-L03 | Tiebeam, truss 6 | 92 | h/s | 1503 | 1594 | 1594 |
| LNG-L04 | West wallpost, truss 6 | 77 | 01 | 1519 | 1594 | 1595 |
| LNG-L05 | West brace, truss 6 | 79 | h/s | 1505 | 1583 | 1583 |
| LNG-L06 | East principal rafter, truss 7 | 72 | h/s | 1507 | 1578 | 1578 |
| LNG-L07 | West principal rafter, truss 7 | 59 | 01 | 1520 | 1577 | 1578 |
| LNG-L08 | Tiebeam, truss 7 | 75 | h/s | ---- | ---- | ---- |
| LNG-L09 | East principal rafter, truss 8 | 109 | h/s | 1489 | 1597 | 1597 |
| LNG-L10 | Tiebeam, truss 8 | 78 | h/s | 1514 | 1591 | 1591 |
| LNG-L11 | East wallpost, truss 8 | 48 | 01 | ---- | ---- | ---- |
| LNG-L12 | West common rafter 5, bay 6 | 55 | h/s | 1539 | 1593 | 1593 |
| LNG-L13 | East common rafter 2, bay 7 | 100 | 03 | 1497 | 1593 | 1596 |
| LNG-L14 | East common rafter 4, bay 7 | 69 | h/s | 1523 | 1591 | 1591 |
| LNG-L15 | East common rafter 6, bay 7 | 106 | 02 | 1490 | 1593 | 1595 |
| Former stable block | | | | | | |
| Main barn - roof & structure | | | | | | |
| LNG-L16 | Tiebeam, truss 1 | 104 | h/s | 1448 | 1551 | 1551 |
| LNG-L17 | Tiebeam, truss 2 | 164 | 25C | 1448 | 1586 | 1611 |
| LNG-L18 | West wallpost, truss 2 | NM | -- | ---- | ---- | ---- |
| LNG-L19 | East principal rafter, truss 3 | 49 | 08 | ---- | ---- | ---- |
| LNG-L20 | Collar, truss 3 | 52 | 01 | 1527 | 1577 | 1578 |
| LNG-L21 | Tiebeam, truss 4 | 63 | h/s | 1501 | 1563 | 1563 |
| LNG-L22 | Tiebeam, truss 5 | 67 | h/s | 1498 | 1564 | 1564 |
| LNG-L23 | West upper main stud, truss 6 | 73 | -- | ---- | ---- | ---- |

| | | | | | | |
|---|---|---|---|---|---|---|
| LNG-L24 | West common rafter 10, bay 1 | 46 | h/s | ---- | ---- | ---- |
| LNG-L25 | West common rafter 7, bay 2 | 53 | 13C | ---- | ---- | ---- |
| LNG-L26 | West common rafter 8, bay 2 | NM | -- | ---- | ---- | ---- |
| LNG-L27 | West upper stud 2, bay 3 | 142 | 10 | 1436 | 1567 | 1577 |
| LNG-L28 | West upper stud 3, bay 3 | 131 | h/s | 1437 | 1567 | 1567 |
| LNG-L29 | West upper stud 1, bay 4 | 116 | -- | 1441 | ---- | 1556 |
| LNG-L30 | East upper stud 2, bay 4 | 128 | 11 | 1445 | 1561 | 1572 |
| Ground-floor ceiling structure | | | | | | |
| LNG-L31 | East joist 5, bay 1 | 54 | 15C | 1558 | 1597 | 1611 |
| LNG-L32 | West joist 1, bay 2 | 67 | 13C | 1545 | 1598 | 1611 |
| LNG-L33 | East joist 2, bay 2 | 67 | -- | 1475 | ---- | 1545 |
| LNG-L34 | East joist 3, bay 2 | 86 | h/s | 1492 | 1577 | 1577 |
| LNG-L35 | West joist 5, bay 2 | 52 | -- | 1541 | ---- | 1592 |
| LNG-L36 | Beam 1 | 75 | h/s | ---- | ---- | ---- |
| LNG-L37 | West joist 1, bay 3 | NM | -- | ---- | ---- | ---- |
| LNG-L38 | West joist 6, bay 3 | 71 | 18 | ---- | ---- | ---- |
| LNG-L39 | West joist 7, bay 3 | 83 | 03 | ---- | ---- | ---- |
| LNG-L40 | West joist 11, bay 4 | 88 | -- | ---- | ---- | ---- |
| South Extension | | | | | | |
| LNG-L41 | East post, truss 7 | 67 | -- | 1315 | ---- | 1381 |
| LNG-L42 | West post, truss 7 | 98 | h/s | 1315 | 1412 | 1412 |
| LNG-L43 | Tiebeam, truss 7 | 44 | h/s | ---- | ---- | ---- |
| LNG-L44 | East brace, truss 7 | 112 | h/s | 1313 | 1424 | 1424 |

*NM = not measured
**h/s = heartwood/sapwood boundary is the last-measured ring
C = complete sapwood retained on sample, last measured ring is the felling date

*Table 2: Results of the cross-matching of site sequence LNGLSQ01 and relevant reference chronologies when the first-ring date is AD 1313 and the last-measured ring date is AD 1424*

| Reference chronology | *t*-value | Span of chronology | Reference |
|---|---|---|---|
| Dragon Hall, Norwich, Norfolk | 7.7 | AD 1289–1426 | Boswijk and Tyers 1998 |
| Abbey Farm barns. Thetford, Norfolk | 5.7 | AD 1237–1428 | Howard *et al* 2000a |
| Marriots Warehouse, Kings Lynn, Norfolk | 5.6 | AD 1310–1583 | Tyers 1999 |
| St Mary Magdalen Church, Wiggenhall, Norfollk | 5.5 | AD 1278–1394 | Bridge 2008a |
| Exeter Guildhall, Exeter, Devon | 5.3 | AD 1453–1498 | Howard *et al* 2000b |
| St Andrew's Church, Owston, Leicestershire | 5.2 | AD 1287–1399 | Howard *et al* 1998 |
| Ightham Mote, Ivy Hatch, Kent | 5.1 | AD 1337–1580 | Howard 2002 unpubl |

*Table 3: Results of the cross-matching of site sequence LNGLSQ02 and relevant reference chronologies when the first-ring date is AD 1436 and the last-measured ring date is AD 1611*

| Reference chronology | *t*-value | Span of chronology | Reference |
|---|---|---|---|
| St Peter and St Paul Church bellframe, Cranfield, Bedfordshire | 10.7 | AD 1342–1469 | Bridge1998 |
| Manor House, Alford, Lincolnshire | 10.3 | AD 1500–1668 | Arnold *et al* 2003 |
| All Saints Church, Mettingham, Suffolk | 9.5 | AD 1528–1598 | Bridge 2009 |
| Bedfield Hall, Suffolk | 9.1 | AD 1473–1627 | Miles *et al* 2007 |
| Astley Castle, Warwickshire | 9.3 | AD 1495–1627 | Howard *et al* 1997 |
| Poorhouse, Framlingham, Suffolk | 8.7 | AD 1426–1585 | Bridge 2008b |
| 7/9 Gracechurch Street, Debenham, Suffolk | 8.7 | AD 1497–1600 | Miles *et al* 2009 |

# FIGURES

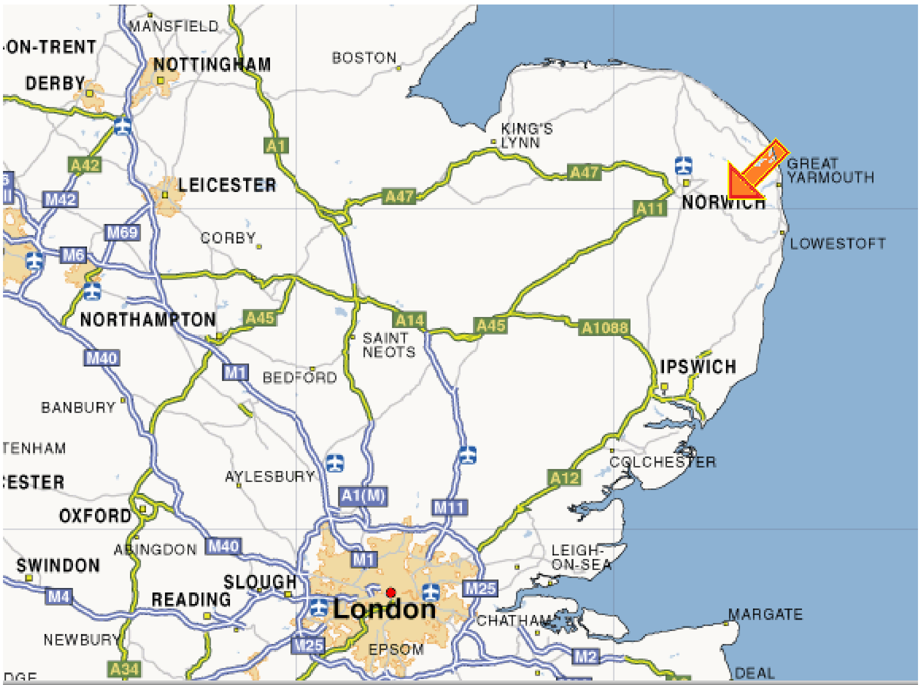


*Figure 1: Map to show the general location of Langley with Hardley, Norfolk, arrowed. © Crown Copyright and database right 2014. All rights reserved. Ordnance Survey Licence number 100024900*

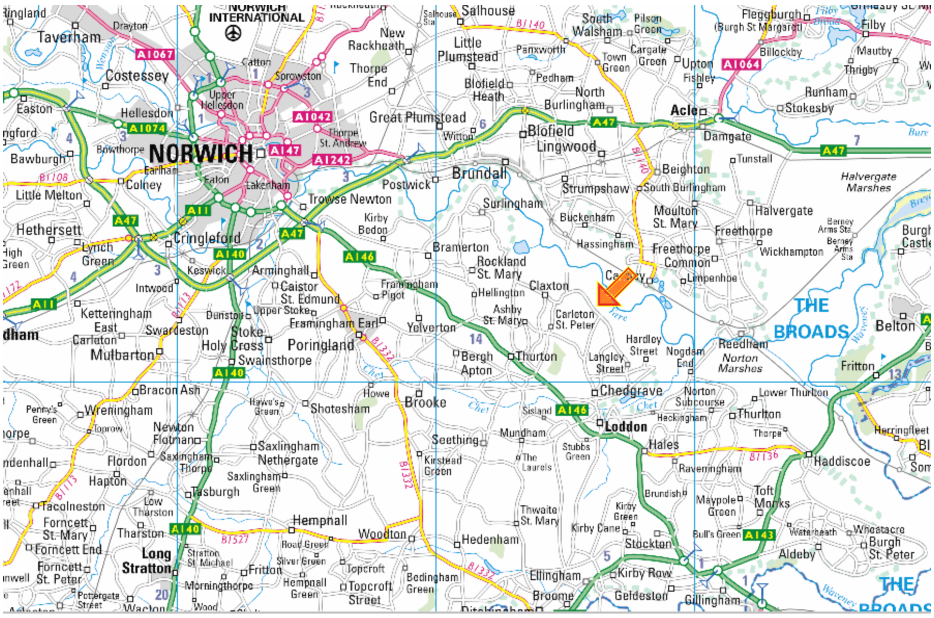


*Figure 2: Map to show the general location of Langley Abbey, Langley with Hardley, Norfolk, arrowed. © Crown Copyright and database right 2014. All rights reserved. Ordnance Survey Licence number 100024900*


*Figure 3: Location of Langley Abbey, Langley with Hardley, Norfolk. © Crown Copyright and database right 2014. All rights reserved. Ordnance Survey Licence number 100024900*

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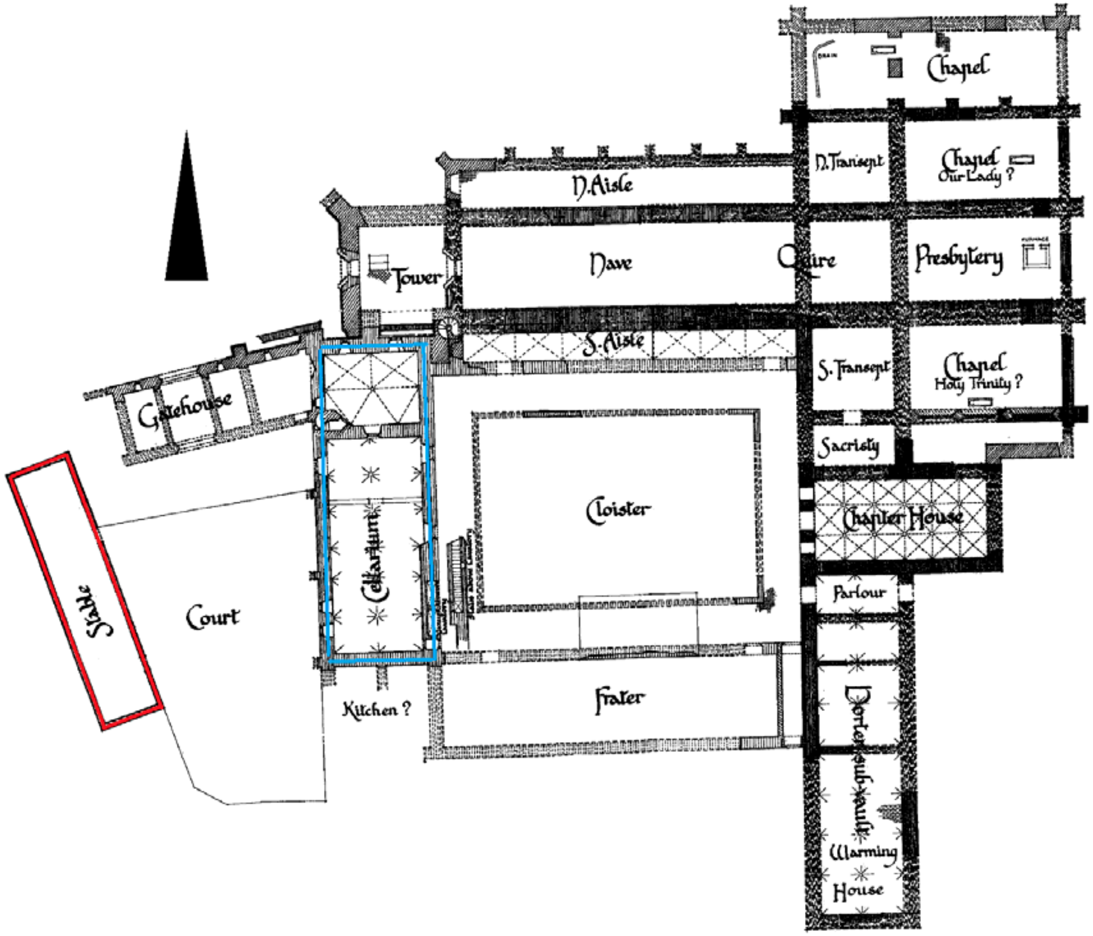


*Figure 4: Ground plan of Langley Abbey with stable block in red and the west range of the cloister in blue (Elliston Erwood 1922)*

*Figure 5: Former west range of the cloister, from the east (Alison Arnold)*

*Figure 6: Former west range of the cloister, photograph taken from the south (Alison Arnold)*

*Figure 7: Former stable block, photograph taken from the north-west (Alison Arnold)*

*Figure 8: Former stable block, truss 3, photograph taken from the north-west (Alison Arnold)*

*Figure 9: Former stable block, trusses 6 (right) and 7 (left) (Alison Arnold)*

*Figure 10: Former stable block, ground-floor ceiling (first-floor frame), photograph taken from the north (Alison Arnold)*

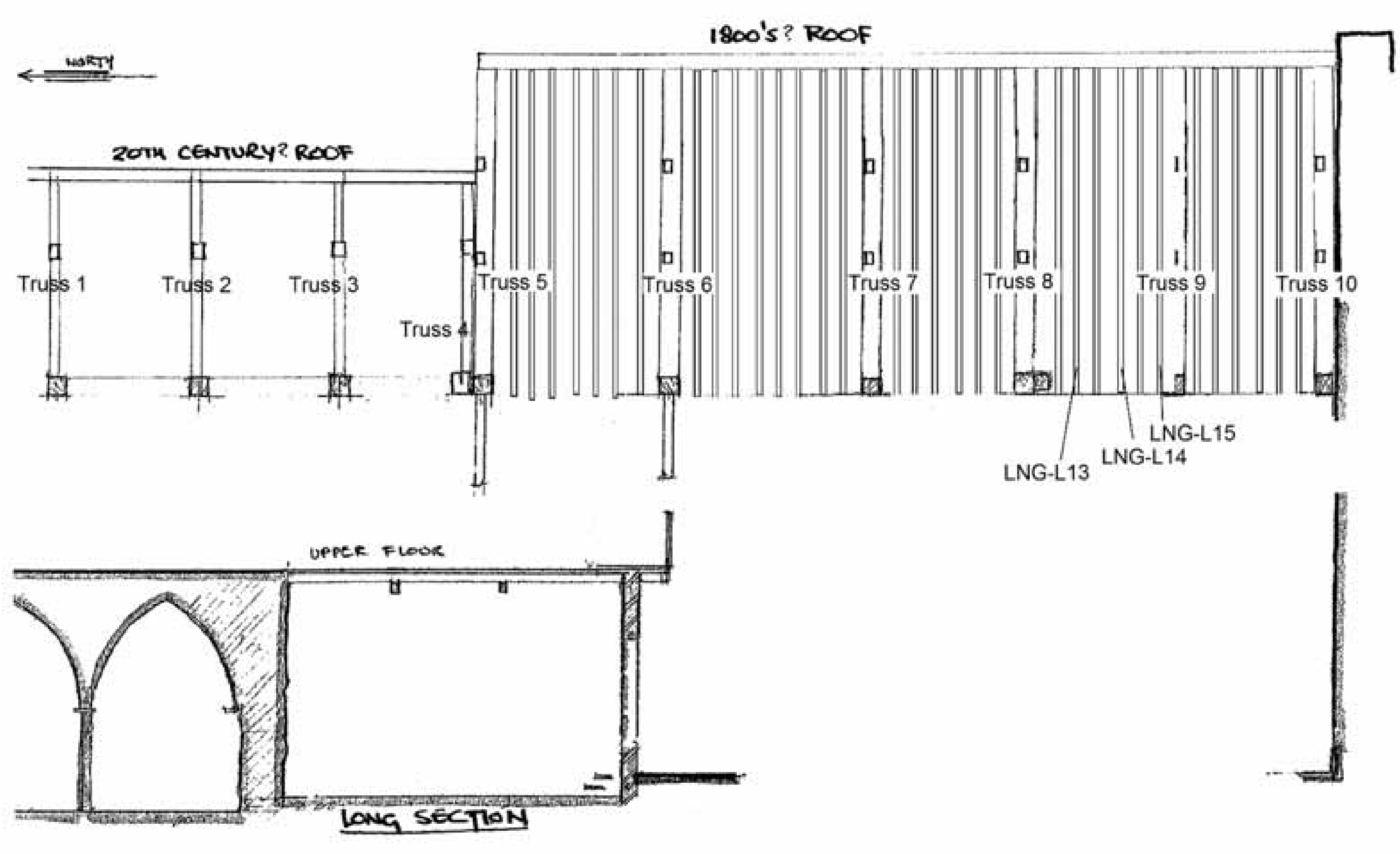


*Figure 11: Former west range of the cloister, long section, east side (inner view), showing the location of samples LNG-L13–15 (Wilson MacGarry Architects)*

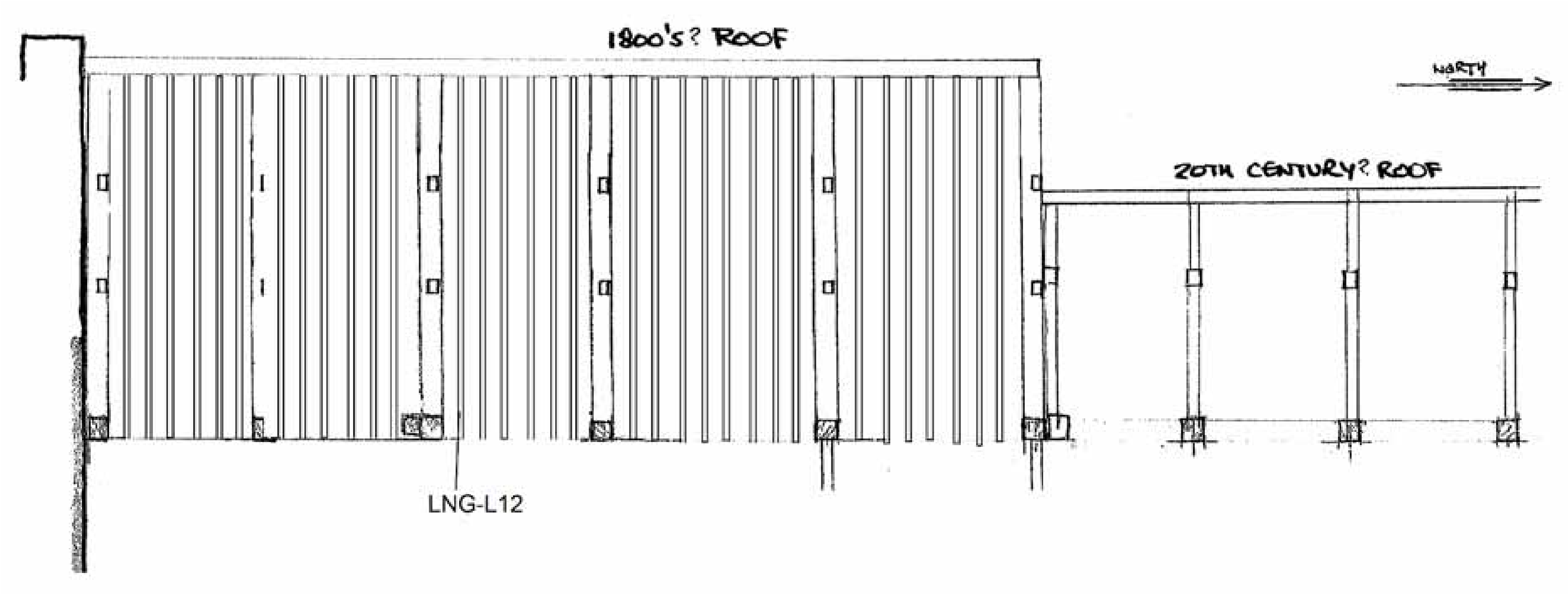


*Figure 12: Former west range of the cloister, long section, west side (inner view), showing the location of sample LNG-L12 (Wilson MacGarry Architects)*

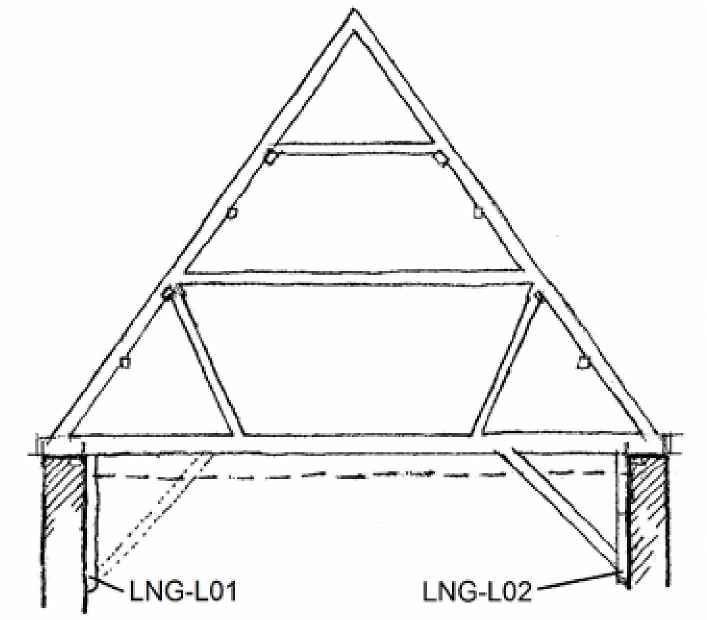


*Figure 13: Former west range of the cloister, truss 5, showing the location of samples LNG-L01 and LNG-L02 (Wilson MacGarry Architects)*

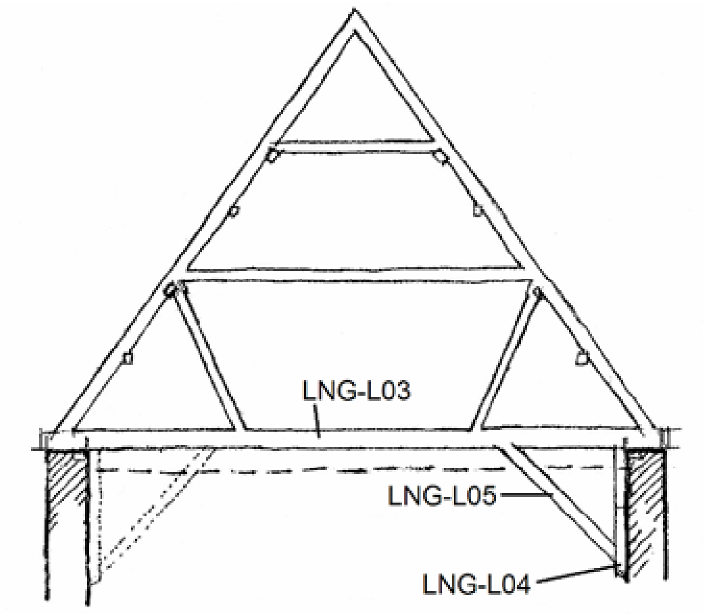


*Figure 14: Former west range of the cloister, truss 6, showing the location of samples LNG-L03–05 (Wilson MacGarry Architects)*

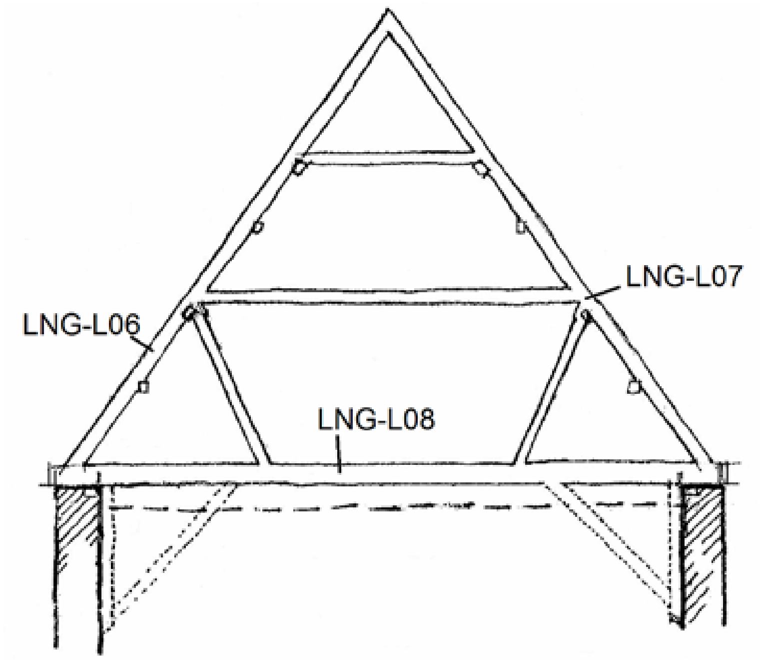


*Figure 15: Former west range of the cloister, truss 7, showing the location of samples LNG-L06–08 (Wilson MacGarry Architects)*

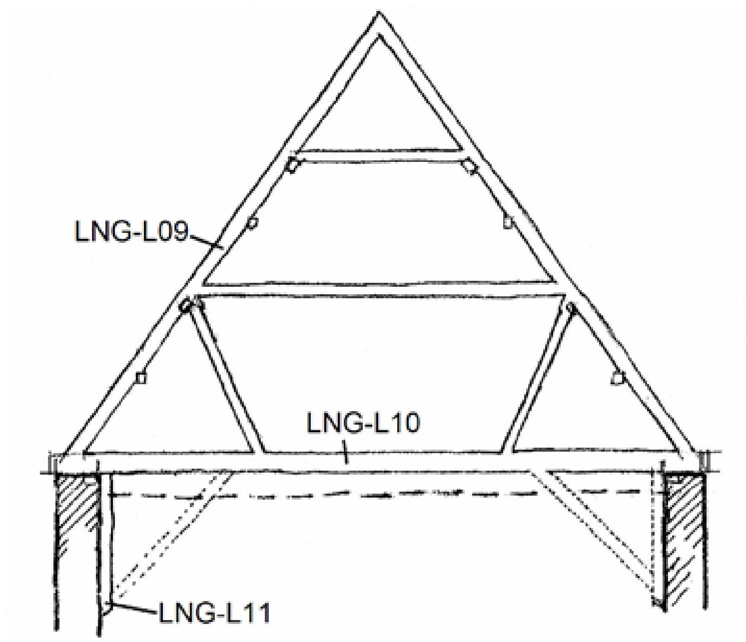


*Figure 16: Former west range of the cloister, truss 8, showing the location of samples LNG-L09–11 (Wilson MacGarry Architects)*

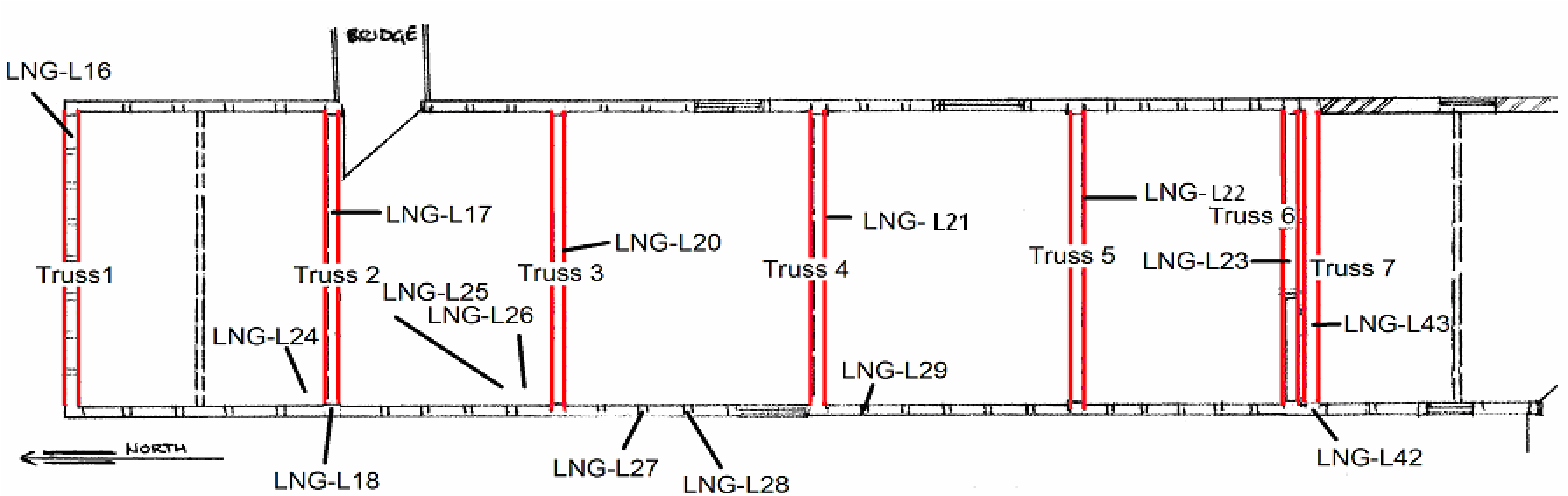


*Figure 17: First-floor plan of the former stable block, showing truss numbering and the location of samples LNG-16–18, LNG-L20–9 and LNG-L42–3 (Wilson MacGarry Architects)*

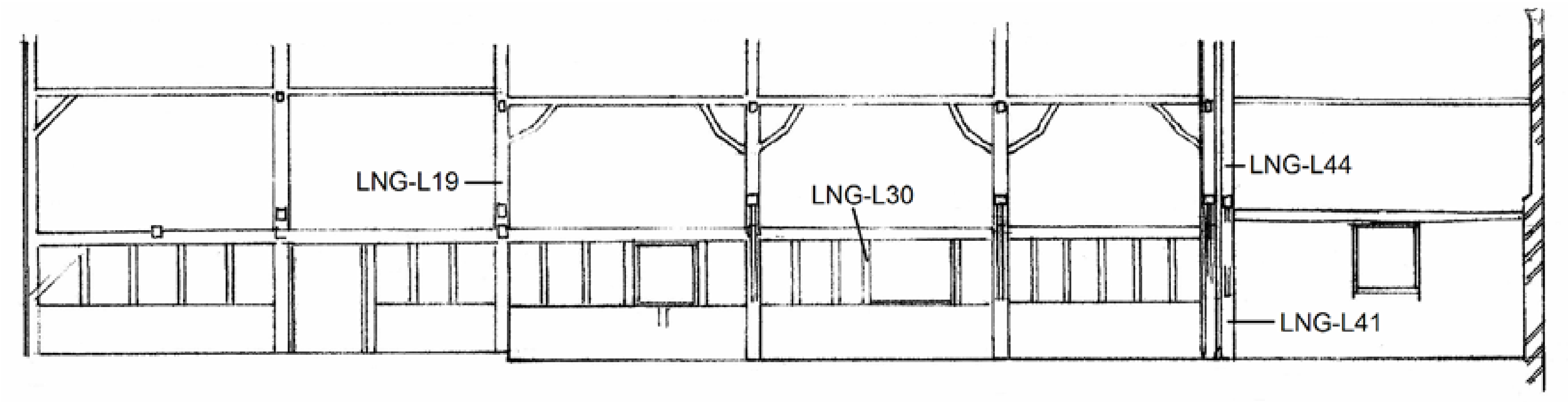


*Figure 18: Long section of east side (inner view) of the former stable block, showing the location of samples LNG-L19, LNG-L30, LNG-L41, and LNG-L44 (Willson MacGarry Architects)*

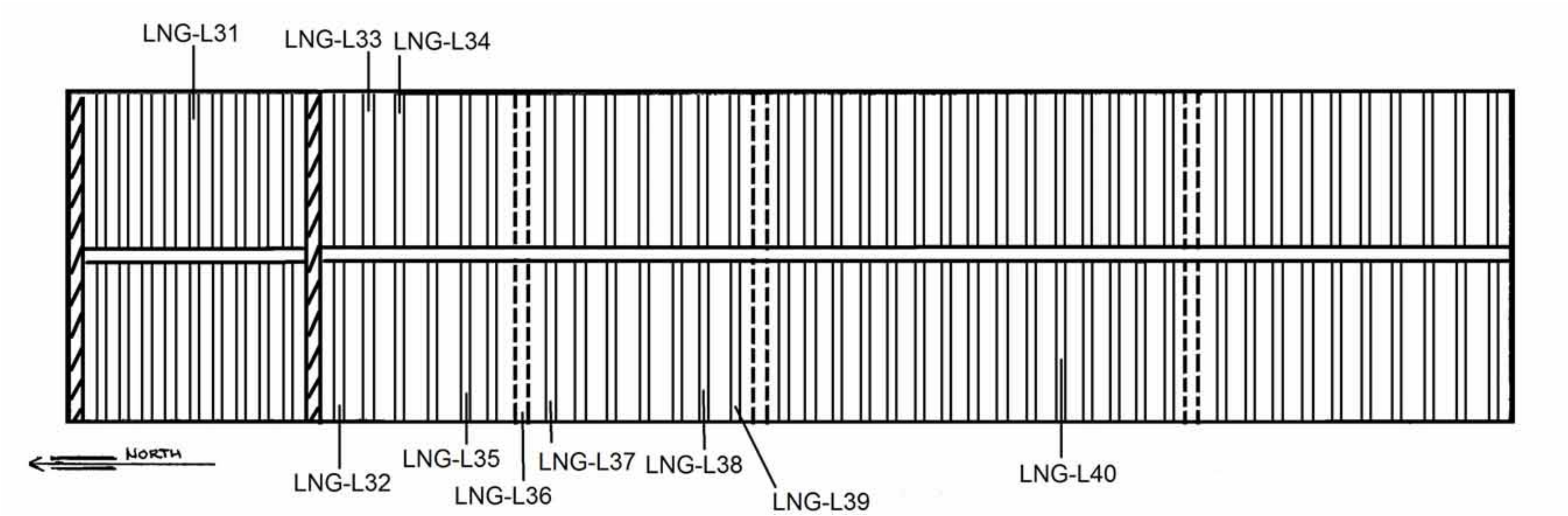


*Figure 19: Sketch of the ground floor of the former stable block, showing the location of samples LNG-L31–40*

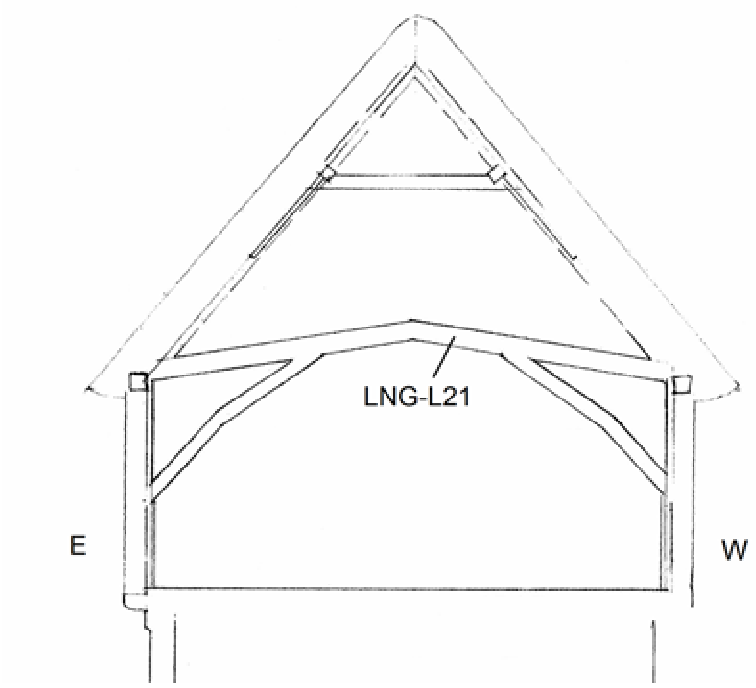


*Figure 20: Former stable block, truss 4, showing the location of sample LNG-L21 (Wilson MacGarrry Architects)*

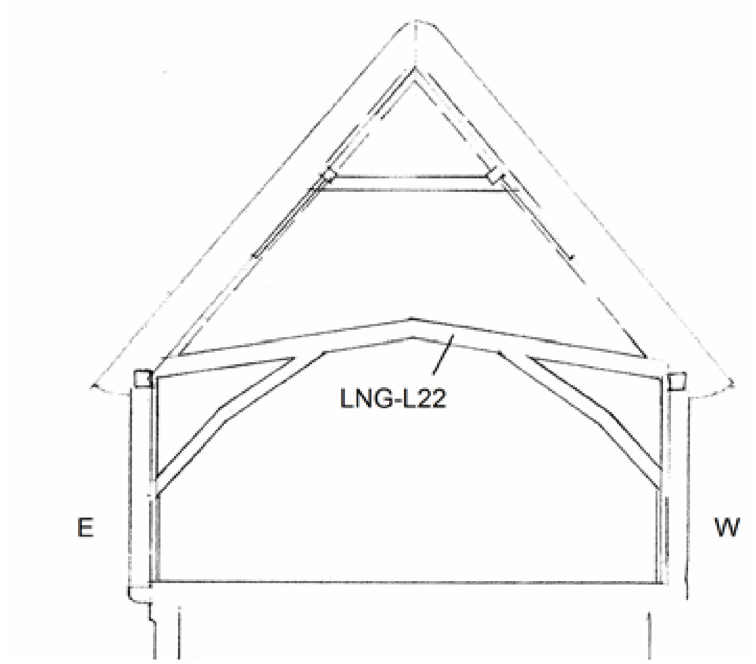


*Figure 21: Former stable block, truss 5, showing the location of sample LNG-L22 (Wilson MacGarry Architects)*

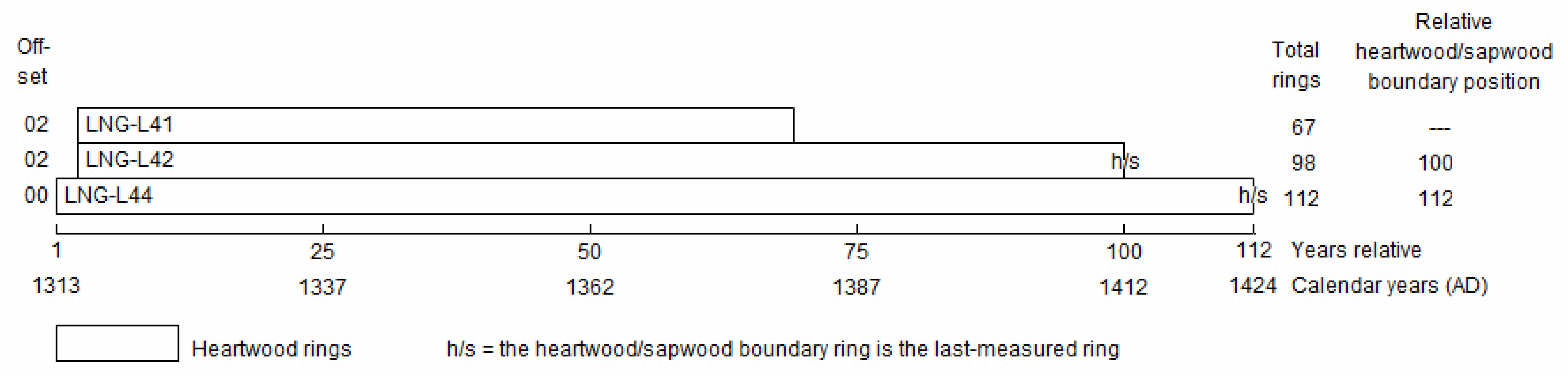


*Figure 22: Bar diagram of samples in site sequence LNGLSQ01*

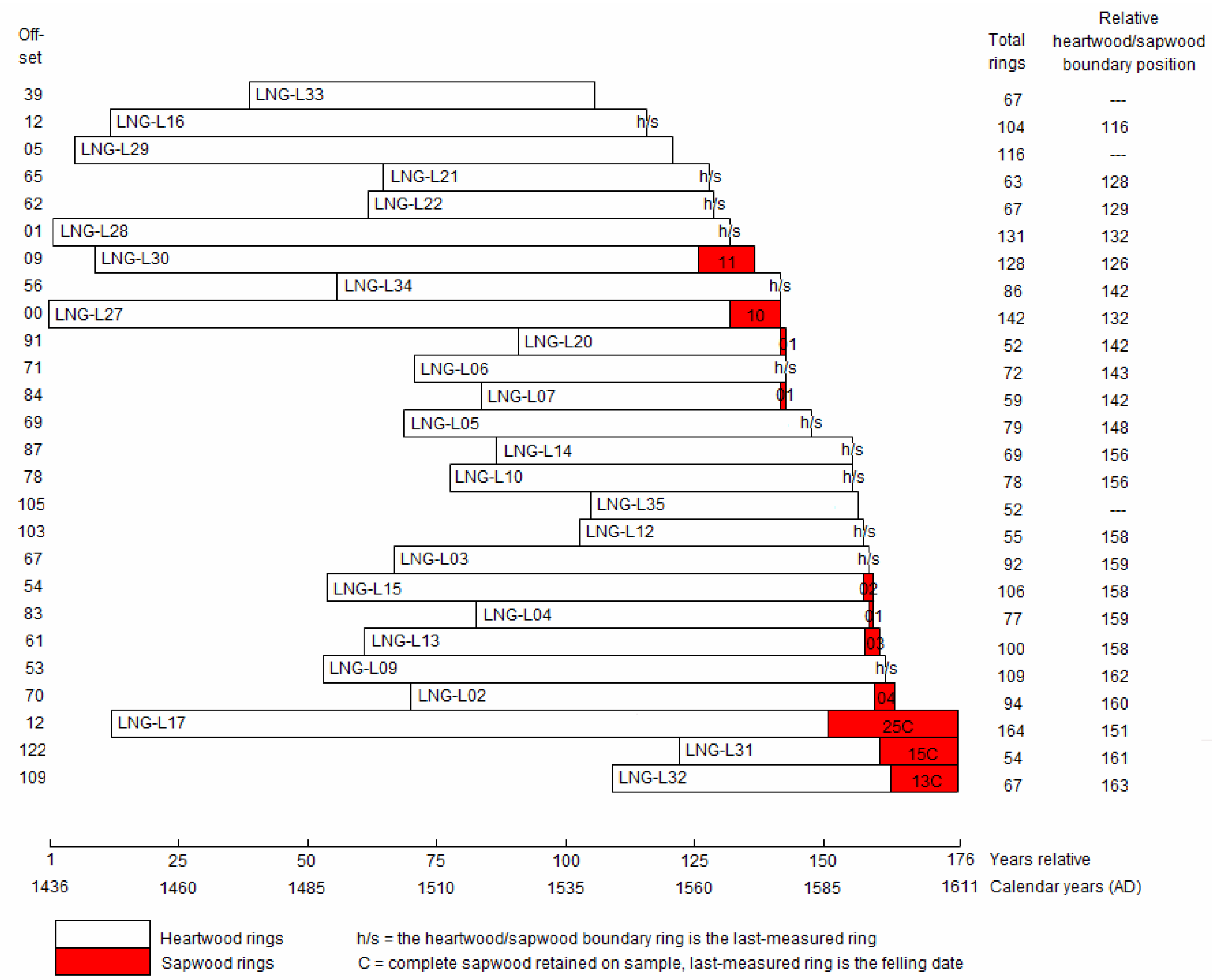


*Figure 23: Bar diagram of samples in site sequence LNGLSQ02*

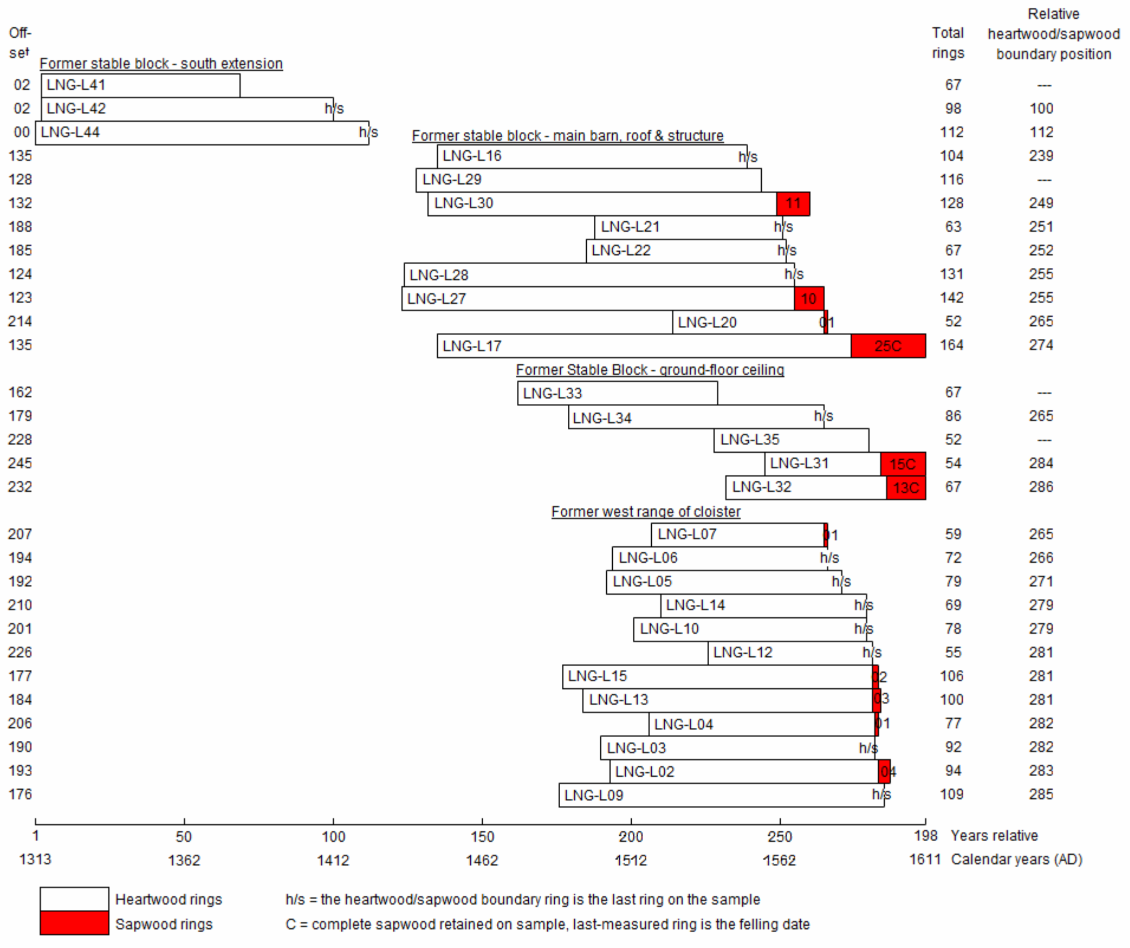


*Figure 24: Bar diagram of all dated samples, sorted by area and heartwood/sapwood boundary ring position*

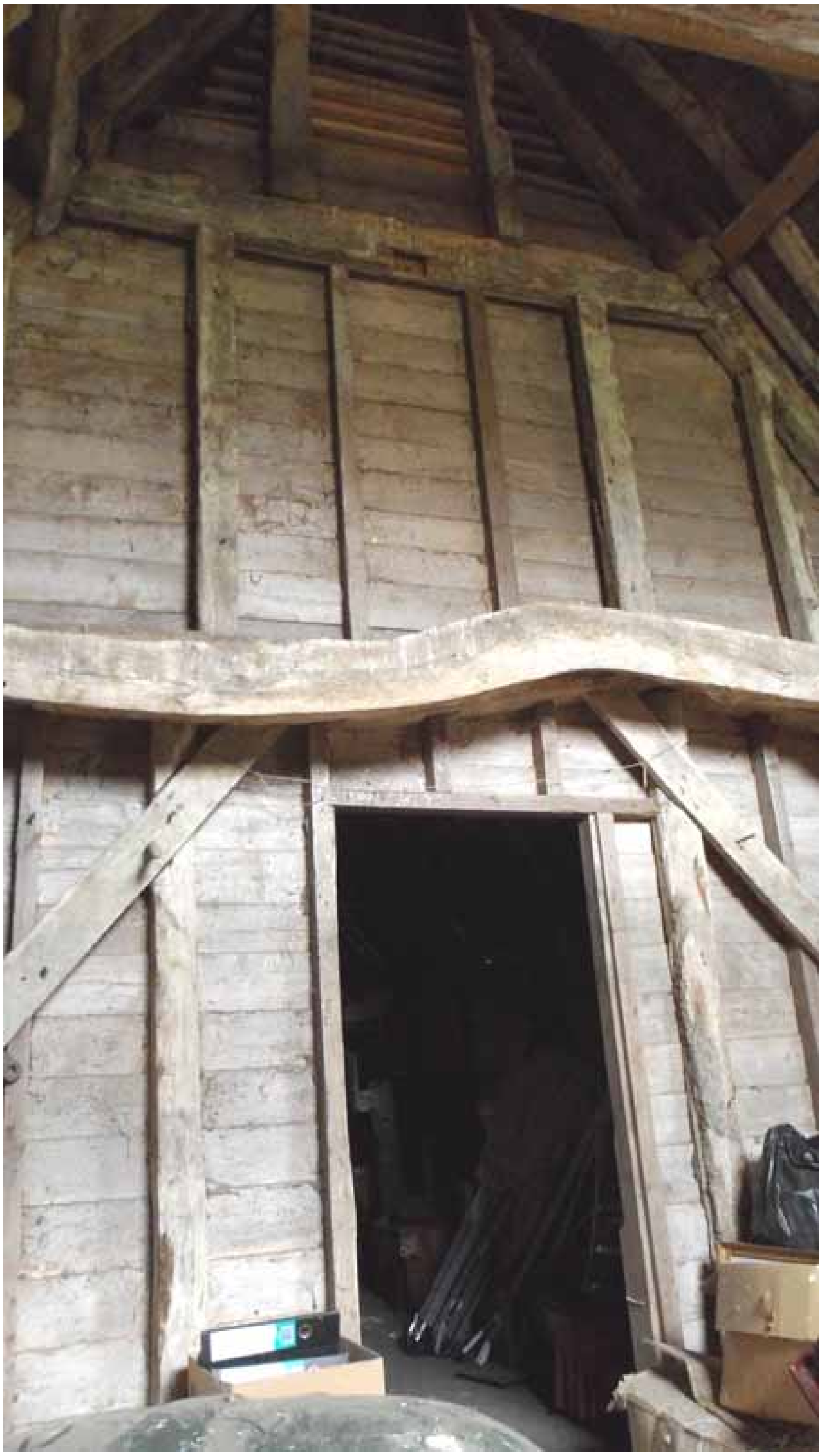

*Figure 25: Truss 7 of the former stable block, with distinctive 'bend', taken from the south (Alison Arnold)*

## DATA OF MEASURED SAMPLES

Measurements in 0.01mm units

LNG-L02A 94
214 232 321 292 232 231 158 134 185 301 320 187 241 117 103 77 123 122 119 103
103 147 148 150 105 171 135 145 151 269 248 251 234 282 297 332 207 252 186 190
141 148 211 188 169 134 133 129 129 135 174 138 122 129 126 130 150 145 102 119
136 114 154 200 231 137 148 197 186 226 190 211 237 235 241 178 176 210 249 251
249 191 143 162 134 143 113 172 181 202 169 164 193 158
LNG-L02B 94
224 243 331 306 235 219 140 121 199 271 299 200 232 121 105 78 116 127 112 105
104 146 147 150 109 172 127 150 149 270 240 256 240 278 298 327 193 239 184 187
150 152 236 199 142 126 121 126 118 143 175 135 121 132 115 128 144 142 102 109
136 112 154 201 223 141 147 193 190 214 192 211 232 235 253 163 167 199 273 259
246 198 153 162 123 148 122 176 184 232 155 177 193 170
LNG-L03A 92
399 384 532 312 453 508 884 718 407 434 353 208 252 228 148 210 297 185 138 193
142 128 94 127 165 160 190 184 262 170 222 164 200 157 120 118 163 130 148 138
100 132 107 72 56 67 85 64 86 63 58 68 101 80 82 81 77 130 87 112
75 74 74 59 44 90 72 109 126 103 118 133 126 122 102 84 63 86 87 107
84 163 102 108 91 82 106 69 55 91 100 124
LNG-L03B 92
419 398 517 301 444 493 928 709 412 435 368 204 258 224 146 213 290 188 141 189
137 126 101 132 171 159 182 173 261 162 189 164 199 154 130 121 148 126 156 144
96 126 110 79 56 70 87 71 72 58 67 65 100 74 86 79 80 130 86 114
72 61 70 63 48 77 83 103 137 105 127 136 114 121 108 78 68 94 83 111
82 154 97 115 85 87 102 72 52 92 92 129
LNG-L04A 77
326 268 202 260 286 220 177 161 233 199 264 192 373 349 347 311 397 321 360 286
331 328 315 182 271 240 203 157 167 182 211 225 186 181 240 188 211 263 215 223
288 248 262 318 265 223 237 189 212 275 241 292 190 222 237 282 368 248 249 221
241 276 208 158 190 295 253 289 218 167 176 178 157 110 137 181 171
LNG-L04B 77
321 262 206 258 289 229 183 148 235 197 267 191 360 346 345 312 395 317 359 284
329 313 319 180 269 243 199 159 160 177 231 224 192 191 238 198 222 271 216 229
282 254 259 313 268 223 238 189 209 275 239 291 194 219 239 284 368 247 251 229
236 278 207 161 186 271 280 287 218 166 174 182 159 112 138 171 172
LNG-L05A 79
173 194 180 185 320 322 287 317 296 275 329 332 224 355 330 174 147 223 193 215
133 178 215 234 239 196 306 248 269 268 381 215 289 302 403 453 482 268 210 252
274 186 118 185 200 204 268 238 279 258 396 288 284 333 311 399 286 283 279 230
256 227 254 324 262 329 304 272 233 255 204 162 149 151 181 194 101 89 96
LNG-L05B 79
179 196 183 181 325 323 293 319 290 277 325 297 218 358 321 170 139 231 219 184
154 178 207 248 240 204 313 254 235 279 367 233 290 298 384 473 473 256 209 255
291 199 136 179 196 218 254 239 280 260 394 271 291 337 324 443 268 299 279 233
270 225 253 292 257 309 303 259 245 242 210 138 150 145 184 190 105 94 95
LNG-L06A 72
238 223 236 351 236 223 314 326 304 395 406 477 285 278 218 265 182 175 264 196
403 224 312 187 539 470 255 204 343 328 333 230 332 472 387 134 168 153 185 309
205 400 507 317 150 247 310 244 483 306 256 202 273 440 305 382 263 165 216 124

136 246 190 211 170 119 161 210 140 129 195 205
LNG-L06B 72
241 229 234 349 235 226 317 323 319 373 413 491 290 287 231 260 180 176 275 200
407 218 311 186 546 474 256 198 338 342 329 234 326 465 372 124 182 156 188 304
206 403 501 315 155 245 308 249 485 302 259 198 265 441 303 384 271 161 214 122
129 249 191 218 168 116 167 220 146 125 190 200
LNG-L07A 59
321 302 237 297 260 239 178 299 215 221 154 340 233 173 151 222 234 223 215 293
387 310 150 153 164 197 407 218 443 670 397 303 294 389 424 640 363 310 216 302
458 329 276 276 167 209 152 178 319 306 257 223 196 262 218 126 121 158 128
LNG-L07B 59
332 289 246 286 250 237 183 289 234 213 173 325 238 163 134 255 206 230 211 281
398 299 147 157 160 195 426 213 441 676 403 298 299 401 432 636 373 313 225 305
450 338 267 270 174 223 154 180 326 307 266 188 194 270 216 135 114 164 127
LNG-L08A 75
300 275 253 235 254 154 251 208 196 139 236 150 190 144 159 145 131 141 92 144
130 155 139 148 105 381 259 160 103 104 65 99 57 80 70 57 82 74 62 77
61 100 79 104 97 107 96 94 133 98 137 128 133 131 113 145 237 338 375 302
185 189 236 267 231 152 159 179 199 161 142 166 217 244 251
LNG-L08B 75
294 283 239 229 254 159 247 208 208 132 261 150 188 146 159 147 134 130 93 148
131 148 143 151 103 385 256 163 104 107 63 86 54 84 66 62 81 73 67 80
57 97 74 103 95 109 91 91 131 103 128 142 119 120 106 144 205 364 367 302
187 192 235 261 232 160 153 179 203 157 148 169 211 248 271
LNG-L09A 109
261 240 199 121 222 235 241 175 147 91 95 198 215 155 151 142 183 167 181 157
162 137 103 85 67 104 119 178 71 205 190 120 78 120 203 182 179 160 155 186
185 169 232 187 217 161 279 171 226 287 349 330 236 258 203 283 363 161 86 170
237 186 202 131 296 225 304 209 193 153 174 323 251 306 254 171 211 230 224 207
261 302 263 269 229 225 269 248 263 213 138 257 178 176 143 194 245 243 174 293
292 182 173 195 229 244 320 297 186
LNG-L09B 109
265 232 200 119 222 231 249 177 146 92 92 179 226 150 158 147 189 178 183 159
154 142 94 83 74 107 116 178 77 203 192 133 72 127 202 180 180 162 155 181
186 167 233 191 216 164 275 173 228 282 351 329 227 261 212 297 350 160 90 179
259 188 209 137 302 227 296 210 193 152 176 317 256 305 253 179 201 240 218 210
261 299 271 274 226 221 275 252 266 213 136 257 177 176 146 196 243 253 174 288
294 173 178 198 241 237 313 315 170
LNG-L10A 78
264 255 329 192 341 328 287 251 308 228 223 175 189 187 202 171 141 206 204 201
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161 175 168 169 141 150 154 160 145 102 93 97 112 146 153 196 219 207 184 200
219 204 180 144 191 183 184 134 146 125 172 172 190 166 166 209 144 187
LNG-L10B 78
257 249 324 190 340 329 298 239 306 227 223 182 189 192 199 166 120 183 179 185
129 233 194 214 179 246 217 193 152 131 149 195 155 112 172 225 187 184 149 176
162 185 164 171 145 144 156 161 138 109 92 98 115 145 148 193 213 211 184 196
219 207 178 145 190 183 185 132 150 118 171 170 192 170 171 196 145 161
LNG-L11A 48
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188 219 295 216 476 598 520 432 257 447 329 210 289 178 246 188 279 159 169 202
230 194 206 166 151 158 128 166
LNG-L11B 48

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234 178 213 165 151 149 135 166
LNG-L12A 55
285 262 256 168 125 141 212 349 204 431 494 437 414 301 360 315 293 242 275 301
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91 147 75 73 101 121 137 121 92 82 106 106 139 132 160
LNG-L12B 55
264 284 248 175 135 140 213 365 181 437 494 440 412 298 358 315 290 249 281 308
247 353 219 274 252 225 219 166 195 215 206 199 125 121 133 140 120 148 140 100
91 151 80 72 99 121 137 122 95 80 106 110 134 128 163
LNG-L13A 100
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57 70 75 55 64 71 75 73 81 90 82 91 90 80 100 88 112 94 115 105
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145 172 199 211 177 191 170 162 125 161 137 157 200 218 218 197 201 218 177 139
124 156 129 233 121 226 151 227 274 225 189 185 183 127 138 168 210 252 252 181
LNG-L13B 100
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59 68 76 57 66 65 72 80 75 95 75 106 81 75 109 91 109 94 118 99
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147 170 209 199 180 183 175 160 121 162 136 169 192 221 217 204 207 217 182 134
129 161 116 247 118 222 154 232 271 223 188 185 181 129 146 161 203 238 260 189
LNG-L14A 69
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135 202 180 161 137 180 209 150 229 175 188 185 239 206 173 185 205 258 214 222
169 174 140 125 132 167 227 255 228 186 179 229 188 160 139 131 136 163 100 126
130 178 197 192 158 138 140 129 135
LNG-L14B 69
104 106 90 121 128 115 97 86 115 112 152 130 168 151 187 165 238 245 218 184
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170 176 137 129 119 169 228 242 225 179 184 227 199 161 133 132 135 162 96 129
128 173 195 195 157 136 133 128 146
LNG-L15A 106
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88 140 96 130 116 160 137 159 129 199 203 174 154 148 207 199 149 129 172 279
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116 123 153 166 202 234
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78 78 50 41 47 58 70 58 34 39 46 49 51 55 44 46 39 44 37 58
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181 204 156 175 158 136 132 103 147 140 165 107 135 112 175 195 155 139 156 133
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LNG-L16A 104
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97 62 62 61 26 50 35 46 63 48 39 39 39 27 35 37 31 34 37 21
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102 89 68 101 80 120 116 130 116 124 129 150 161 149 120 120 145 147 119 120

158 182 149 161
LNG-L16B 104
112 140 136 135 98 108 128 144 181 142 198 158 154 151 151 124 123 100 84 93
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94 53 57 67 35 42 27 62 60 43 38 34 44 30 42 28 38 37 32 28
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106 85 68 104 79 124 114 136 122 121 116 160 170 150 121 124 135 150 118 121
153 178 128 135
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127 181 182 148 127 135 146 170 193 217 193 144 154 126 139 107 97 99 115 105
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80 104 77 65 39 45 39 50 57 48 40 35 36 34 34 35 33 30 36 27
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57 50 40 54 55 57 58 86 63 64 57 92 81 76 66 60 77 93 70 86
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102 121 148 127 114 130 137 124 97 71 110 81 114 70 115 99 142 156 151 82
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109 88 51 70
LNG-L17B 139
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81 103 65 75 42 40 35 55 64 40 40 37 38 28 33 31 43 31 31 25
31 37 29 31 35 36 43 41 43 30 49 51 41 41 34 35 36 40 56 50
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121 157 119 139 109 122 101 142 109 108 112 122 144 114 121 121 105 70 103 87
105 123 156 125 117 132 135 126 95 75 110 81 111 73 117 98 150 154 133
LNG-L19A 49
634 593 522 369 437 380 526 395 385 418 540 363 402 361 412 432 458 342 289 336
326 418 299 314 217 165 156 258 278 273 85 104 110 211 158 181 151 217 293 242
181 300 186 258 255 253 291 284 157
LNG-L19B 49
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315 420 299 313 225 162 153 247 277 271 83 99 116 197 165 173 158 227 309 236
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LNG-L20A 52
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163 182 306 140 157 131 250 242 239 181 149 129 137 325 160 182 141 88 77 93
109 118 136 285 183 161 155 246 199 175 276 351
LNG-L20B 52
507 448 441 256 463 361 380 364 433 244 275 324 312 241 266 236 197 209 263 157
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121 118 126 292 195 171 130 245 193 185 281 342
LNG-L21A 63
312 377 392 474 475 429 385 344 440 475 376 423 512 326 360 326 257 367 392 347
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228 189 230 310 351 184 128 197 361 246 198 148 133 137 153 137 119 151 129 197
151 222 173
LNG-L21B 63
322 366 372 465 455 426 376 348 425 482 355 415 518 320 373 307 268 367 373 342
299 288 290 223 281 292 378 301 277 226 327 280 255 251 301 236 206 233 282 271
235 177 245 318 349 177 120 210 360 236 208 138 142 135 149 135 123 142 127 197
165 205 163
LNG-L22A 67

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292 330 330 279 210 260 324 387 217 102 184 258 216 255 179 214 205 212 178 162
192 180 267 178 250 200 229
LNG-L22B 67
352 361 398 437 493 411 588 535 493 474 426 601 536 437 471 568 514 419 504 392
539 562 566 570 551 254 181 217 201 270 279 216 188 260 271 234 231 315 250 238
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198 184 264 194 242 199 207
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151 115 153 184 195 119 105 110 107 114 122 84 63 69 80 107 115 155 234 360
187 105 107 156 144 213 175 275 183 136 123 151 129
LNG-L23B 73
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150 120 146 180 203 124 108 111 108 117 119 84 65 70 78 101 125 160 236 365
182 105 110 156 149 210 178 273 175 137 122 154 133
LNG-L24A 46
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182 194 188 162 158 104 163 150 185 120 126 183 157 195 201 193 204 164 141 163
209 253 164 92 80 176
LNG-L24B 46
252 204 219 252 242 232 243 247 168 186 268 223 189 232 192 285 240 96 85 138
180 204 179 161 153 106 170 149 181 123 124 186 160 190 198 191 215 159 143 168
211 252 157 89 95 164
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201 123 221 236 156 206 135 209 168 186 160 128 140 164 173 152 179 157 206 100
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284 330 260 207 117 118 167 185 125 184 122 191 201
LNG-L25B 53
211 115 228 232 154 203 136 210 170 181 158 135 134 163 172 155 176 151 208 101
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320 279 278 208 117 120 159 184 126 183 118 185 204
LNG-L27A 142
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90 70 94 69 70 102 47 64 78 72 47 46 69 38 77 46 43 43 44 51
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113 82 87 98 100 155 149 110 154 100 126 118 106 143 119 98 98 63 67 53
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195 225 149 329 294 192 149 180 153 202 155 139 189 236 152 221 165 174 188 209
196 168 109 167 200 111 158 132 93 121 142 155 181 218 211 152 176 170 146 209
151 166
LNG-L27B 142
267 273 179 172 166 204 209 185 74 120 94 114 73 105 81 71 67 65 83 87
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117 177

LNG-L28A 131
278 368 235 194 149 194 176 87 130 136 137 76 122 83 67 78 91 119 97 92
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156 116 125 121 97 141 107 106 94 73 104
LNG-L28B 131
278 372 253 205 154 204 174 93 134 138 132 81 123 82 68 76 89 121 103 84
61 104 75 68 133 68 78 95 118 79 53 103 62 100 65 77 47 52 51 55
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LNG-L29A 116
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LNG-L29B 116
172 204 163 87 126 136 145 64 132 71 63 66 98 109 99 93 70 98 102 91
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69 79 90 74 130 131 105 127 109 86 194 128 169 145 204 257 285 215 327 305
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LNG-L30A 128
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49 52 58 62 74 61 60 72 67 60 58 63 55 77 72 84 46 87 79 54
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165 147 131 135 166 117 167 110 129 123 131 120 112 90 106 119 92 113 78 71
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LNG-L30B 128
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99 44 53 59 60 59 43 46 44 41 39 43 45 22 34 38 51 35 26 35
41 35 49 44 47 35 68 46 54 39 40 62 47 42 38 32 52 44 56 60
52 48 58 66 76 58 69 58 73 56 51 78 57 77 72 82 48 84 87 51
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221 189 160 145 141 208 127 123 166 210 148 132 155 172
LNG-L31B 54
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171 136 235 135 164 164 188 221 276 157 178 199 156 160 196 196 189 223 130 196

230 184 166 138 165 193 136 118 193 182 153 150 157 165
LNG-L32A 67
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131 181 213 151 147 166 254
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239 248 197 288 289 277 221 263 259 267 238 227 201 193 214 244 198 191 212 168
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129 112 126 149 162 140 131
LNG-L33B 67
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227 256 228 137 130 186 171 194 154 246 151 178 223 168 160 144 140 125 168 117
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LNG-L34A 86
367 242 388 328 391 312 168 147 215 169 199 147 232 140 152 173 148 141 148 113
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LNG-L35A 52
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189 183 191 199 226 260 230 293 323 297 238 311 276 303 285 256 231 226 283 326
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181 175 137 190 213 232 162 194 198 160 155 195
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227 268 270 265 227 152 151 258 150 294 264 267 227 186 208 154 198 210 243 192
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157 117 91 111 139 207 178 142 145 109 133 115 134 169 182
LNG-L36B 75
157 172 92 86 93 125 169 169 148 143 174 198 185 215 222 246 201 189 312 233
220 267 277 258 229 156 150 266 146 294 256 261 229 188 197 153 196 211 245 190
188 90 135 127 186 176 129 96 128 98 133 131 105 126 162 140 116 134 127 119
153 122 94 110 133 212 183 140 144 114 126 122 128 164 190
LNG-L38A 71
159 211 192 121 262 172 318 245 189 181 203 177 136 103 208 112 147 272 200 298

427 412 599 273 356 350 329 268 276 211 319 170 304 229 230 121 110 136 154 139
140 186 276 167 164 132 127 273 218 247 289 227 217 158 147 104 157 190 185 142
187 175 186 185 152 189 223 127 84 82 86
LNG-L38B 71
162 214 204 131 254 175 321 243 198 192 200 183 128 127 203 113 186 286 209 318
430 415 594 279 348 357 328 268 279 214 321 173 303 231 228 143 110 136 155 136
143 187 274 169 164 136 128 268 212 251 289 226 188 166 138 110 170 190 139 173
197 162 180 181 157 192 214 135 74 86 105
LNG-L39A 83
254 295 301 209 143 159 271 196 158 166 189 142 159 143 168 155 166 170 214 164
143 143 122 112 141 259 300 179 152 229 219 229 136 114 151 143 157 102 123 151
126 234 186 141 109 134 176 117 160 137 153 140 167 121 116 111 126 117 118 77
48 58 77 93 90 161 211 243 140 95 82 115 191 207 171 172 132 149 108 151
186 136 115
LNG-L39B 83
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138 134 132 101 122 269 295 179 151 234 218 227 138 118 142 144 161 109 110 147
137 230 197 137 118 136 176 108 167 130 153 146 162 117 127 116 123 117 121 71
52 58 73 97 86 164 210 220 146 94 83 109 173 196 168 188 145 130 115 159
198 147 120
LNG-L40A 88
118 266 319 540 718 616 566 284 389 287 349 257 356 165 118 59 175 244 127 101
45 24 20 21 31 24 23 26 27 29 25 26 31 23 23 29 40 24 21 30
21 11 44 76 208 89 199 103 111 85 50 92 121 72 53 42 57 54 90 76
141 76 168 109 173 166 125 209 254 271 194 234 213 115 165 139 105 198 139 271
243 210 169 182 166 203 149 318
LNG-L40B 88
127 266 328 536 734 605 567 280 398 284 350 258 343 169 99 61 168 252 134 98
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31 23 26 74 207 74 184 81 98 70 56 85 122 69 53 47 53 58 89 72
143 80 165 107 173 171 138 215 280 296 205 231 220 112 171 135 104 198 143 222
191 175 164 192 162 213 153 268
LNG-L41A 67
275 323 189 111 116 185 184 147 158 91 65 48 69 62 64 43 42 34 36 126
132 124 78 112 229 200 132 160 72 203 234 151 144 144 188 325 328 139 198 142
171 195 222 145 101 235 207 99 68 81 67 71 86 172 177 141 132 184 123 229
272 252 232 200 148 142 241
LNG-L41B 67
275 336 177 116 116 143 187 125 141 103 63 60 56 68 69 34 40 44 41 123
131 131 80 113 232 198 133 155 81 204 230 155 149 139 188 322 340 135 192 149
182 197 221 141 95 238 212 104 74 85 74 79 92 180 167 138 134 194 123 229
273 267 226 205 147 145 275
LNG-L42A 98
494 444 315 178 278 336 367 337 329 202 149 84 130 117 108 59 38 46 49 119
143 118 80 118 183 123 128 135 68 100 111 57 91 85 121 250 355 139 167 97
143 133 109 72 65 110 89 56 43 58 61 79 69 95 99 75 89 108 58 149
111 109 74 105 130 84 106 138 145 56 45 57 89 157 92 169 106 76 76 122
86 166 78 139 147 178 107 126 117 54 46 29 32 45 36 44 63 62
LNG-L42B 98
499 442 313 182 280 348 382 338 335 203 141 90 131 112 119 53 37 49 54 113
145 119 81 110 179 138 124 141 69 94 118 59 95 88 116 257 359 145 168 111
147 119 103 69 65 111 87 49 58 68 59 80 69 94 95 67 95 115 51 153
116 104 86 107 129 82 114 137 145 54 41 62 81 148 81 162 95 77 79 117

90 161 89 139 151 185 118 126 118 43 42 25 25 39 41 46 55 61
LNG-L43A 44
194 178 164 303 590 341 348 472 409 214 333 306 383 390 163 117 261 348 349 219
338 411 449 465 316 129 102 69 120 129 156 112 136 223 311 214 337 309 142 96
118 137 144 159
LNG-L43B 44
191 181 163 303 582 339 345 486 422 199 338 308 367 382 151 108 234 337 344 217
338 404 453 459 303 119 92 76 116 126 138 117 138 214 311 211 324 317 132 100
112 134 173 183
LNG-L44A 112
109 212 254 249 149 129 106 96 130 102 111 78 53 47 92 79 86 69 63 70
65 100 104 79 95 90 83 75 86 95 75 101 120 75 74 62 96 133 166 131
131 109 125 157 158 130 106 185 125 251 288 198 166 122 194 230 238 203 161 190
141 179 267 366 276 278 185 160 240 249 156 81 111 148 172 177 141 191 125 102
152 163 127 184 165 305 225 235 246 165 179 64 58 47 40 36 36 44 47 51
74 74 77 77 130 182 128 176 260 207 240 182
LNG-L44B 112
118 206 257 257 168 127 95 98 120 113 103 79 56 45 81 76 65 73 68 63
63 101 105 86 90 97 84 77 84 99 75 97 115 78 75 64 95 135 162 132
137 105 128 162 159 131 104 182 135 246 279 201 171 116 195 233 241 205 163 198
136 180 269 365 277 277 188 159 247 248 152 78 117 151 180 175 145 181 135 98
166 164 120 183 174 299 227 241 242 162 181 61 54 46 43 47 33 39 44 55
71 75 82 71 123 179 136 175 253 211 243 182

# APPENDIX: TREE-RING DATING

## The Principles of Tree-Ring Dating

Tree-ring dating, or dendrochronology as it is known, is discussed in some detail in the Laboratory's Monograph, *An East Midlands Master Tree-Ring Chronology and its uses for dating Vernacular Building* (Laxton and Litton 1988) and *Dendrochronology: Guidelines on Producing and Interpreting Dendrochronological Dates* (English Heritage 1998). Here we will give the bare outlines. Each year an oak tree grows an extra ring on the outside of its trunk and all its branches just inside its bark. The width of this annual ring depends largely on the weather during the growing season, about April to October, and possibly also on the weather during the previous year. Good growing seasons give rise to relatively wide rings, poor ones to very narrow rings and average ones to relatively average ring widths. Since the climate is so variable from year to year, almost random-like, the widths of these rings will also appear random-like in sequence, reflecting the seasons. This is illustrated in Figure A1 where, for example, the widest rings appear at irregular intervals. This is the key to dating by tree rings, or rather, by their widths. Records of the average ring widths for oaks, one for each year for the last 1000 years or more, are available for different areas. These are called master chronologies. Because of the random-like nature of these sequences of widths, there is usually only one position at which a sequence of ring widths from a sample of oak timber with at least 70 rings will match a master. This will date the timber and, in particular, the last ring.

If the bark is still on the sample, as in Figure A1, then the date of the last ring will be the date of felling of the oak from which it was cut. There is much evidence that in medieval times oaks cut down for building purposes were used almost immediately, usually within the year or so (Rackham 1976). Hence if bark is present on several main timbers in a building, none of which appear reused or are later insertions, and if they all have the same date for their last ring, then we can be quite confident that this is the date of construction or soon after. If there is no bark on the sample, then we have to make an estimate of the felling date; how this is done is explained below.

## The Practice of Tree-Ring Dating at the Nottingham Tree-Ring Dating Laboratory

1. Inspecting the Building and Sampling the Timbers. Together with a building historian the timbers in a building are inspected to try to ensure that those sampled are not reused or later insertions. Sampling is almost always done by coring into the timber, which has the great advantage that we can sample in situ timbers and those judged best to give the date of construction, or phase of construction if there is more than one in the building. The timbers to be sampled are also inspected to see how many rings they have. We normally look for timbers with at least 70 rings, and preferably more. With fewer rings than this, 50 for example, sequences of widths become difficult to match to a unique

position within a master sequence of ring widths and so are difficult to date (Litton and Zainodin 1991). The cross-section of the rafter shown in Figure A2 has about 120 rings; about 20 of which are sapwood rings – the lighter rings on the outside. Similarly the core has just over 100 rings with a few sapwood rings.

To ensure that we are getting the date of the building as a whole, or the whole of a phase of construction if there is more than one, about 8–10 samples per phase are usually taken. Sometimes we take many more, especially if the construction is complicated. One reason for taking so many samples is that, in general, some will fail to give a date. There may be many reasons why a particular sequence of ring widths from a sample of timber fails to give a date even though others from the same building do. For example, a particular tree may have grown in an odd ecological niche, so odd indeed that the widths of its rings were determined by factors other than the local climate! In such circumstances it will be impossible to date a timber from this tree using the master sequence whose widths, we can assume, were predominantly determined by the local climate at the time.

Sampling is done by coring into the timber with a hollow corer attached to an electric drill and usually from its outer rings inwards towards where the centre of the tree, the pith, is judged to be. An illustration of a core is shown in Figure A2; it is about 150mm long and 10mm diameter. Great care has to be taken to ensure that as few as possible of the outer rings are lost in coring. This can be difficult as these outer rings are often very soft (see below on sapwood). Each sample is given a code which identifies uniquely which timber it comes from, which building it is from and where the building is located. For example, CRO-A06 is the sixth core taken from the first building (A) sampled by the Laboratory in Cropwell Bishop. Where it came from in that building will be shown in the sampling records and drawings. No structural damage is done to any timbers by coring, nor does it weaken them.

During the initial inspection of the building and its timbers the dendrochronologist may come to the conclusion that, as far as can be judged, none of the timbers have sufficient rings in them for dating purposes and may advise against sampling to save further unwarranted expense.

All sampling by the Laboratory is undertaken according to current Health and Safety Standards. The Laboratory's dendrochronologists are insured.

*Figure A1: A wedge of oak from a tree felled in 1976. It shows the annual growth rings, one for each year from the innermost ring to the last ring on the outside just inside the bark. The year of each ring can be determined by counting back from the outside ring, which grew in 1976*

*Figure A2: Cross-section of a rafter, showing sapwood rings in the left-hand corner, the arrow points to the heartwood/sapwood boundary (H/S); and a core with sapwood; again the arrow is pointing to the H/S. The core is about the size of a pencil*

*Figure A3: Measuring ring widths under a microscope. The microscope is fixed while the sample is on a moving platform. The total sequence of widths is measured twice to ensure that an error has not been made. This type of apparatus is needed to process a large number of samples on a regular basis*


*Figure A4: Three cores from timbers in a building. They come from trees growing at the same time. Notice that, although the sequences of widths look similar, they are not identical. This is typical*

2. Measuring Ring Widths. Each core is sanded down with a belt sander using medium-grit paper and then finished by hand with flourgrade-grit paper. The rings are then clearly visible and differentiated from each other with a result very much like that shown in Figure A2. The core is then mounted on a movable table below a microscope and the ring-widths measured individually from the innermost ring to the outermost. The widths are automatically recorded in a computer file as they are measured (see Fig A3).

3. Cross-Matching and Dating the Samples. Because of the factors besides the local climate which may determine the annual widths of a tree's rings, no two sequences of ring widths from different oaks growing at the same time are exactly alike (Fig A4). Indeed, the sequences may not be exactly alike even when the trees are growing near to each other. Consequently, in the Laboratory we do not attempt to match two sequences of ring widths by eye, or graphically, or by any other subjective method. Instead, it is done objectively (ie statistically) on a computer by a process called cross-matching. The output from the computer tells us the extent of correlation between two sample sequences of widths or, if we are dating, between a sample sequence of widths and the master, at each relative position of one to the other (offsets). The extent of the correlation at an offset is determined by the *t*-value (defined in almost any introductory book on statistics). That offset with the maximum *t*-value among the *t*-values at all the offsets will be the best candidate for dating one sequence relative to the other. If one of these is a master chronology, then this will date the other. Experiments carried out in the past with sequences from oaks of known date suggest that a *t*-value of at least 4.5, and preferably at least 5.0, is usually adequate for the dating to be accepted with reasonable confidence (Laxton and Litton 1988; Laxton *et al* 1988; Howard *et al* 1984–1995).

This is illustrated in Figure A5 with timbers from one of the roofs of Lincoln Cathedral. Here four sequences of ring widths, LIN-C04, 05, 08, and 45, have been cross-matched with each other. The ring widths themselves have been omitted in the bar diagram, as is usual, but the offsets at which they best cross-match each other are shown; eg the sequence of ring widths of C08 matches the sequence of ring widths of C45 best when it is at a position starting 20 rings after the first ring of C45, and similarly for the others. The actual t-values between the four at these offsets of best correlations are in the matrix. Thus at the offset of +20 rings, the *t*-value between C45 and C08 is 5.6 and is the maximum found between these two among all the positions of one sequence relative to the other.

It is standard practice in our Laboratory first to cross-match as many as possible of the ring-width sequences of the samples in a building and then to form an average from them. This average is called a site sequence of the building being dated and is illustrated in Figure A5. The fifth bar at the bottom is a site sequence for a roof at Lincoln Cathedral and is constructed from the matching sequences of the four timbers. The site sequence width for each year is the average of the widths in each of the sample sequences which has a width for that year. Thus in Fig A5 if the widths shown are 0.8mm for C45, 0.2mm for C08, 0.7mm for C05, and 0.3mm for C04, then the corresponding width of the site sequence is the average of these, 0.55mm. The actual sequence of widths of this site sequence is stored on the computer. The reason for creating site sequences is that it is usually easier to date an average sequence of ring widths with a master sequence than it is to date the individual component sample sequences separately.

The straightforward method of cross-matching several sample sequences with each other one at a time is called the 'maximal *t*-value' method. The actual method of cross-matching a group of sequences of ring-widths used in the Laboratory involves grouping and averaging the ring-width sequences and is called the 'Litton-Zainodin Grouping Procedure'. It is a modification of the straightforward method and was successfully developed and tested in the Laboratory and has been published (Litton and Zainodin 1991; Laxton *et al* 1988).

4. Estimating the Felling Date. As mentioned above, if the bark is present on a sample, then the date of its last ring is the date of the felling of its tree (or the last full year before felling, if it was felled in the first three months of the following calendar year, before any new growth had started, but this is not too important a consideration in most cases). The actual bark may not be present on a timber in a building, though the dendrochronologist who is sampling can often see from its surface that only the bark is missing. In these cases the date of the last ring is still the date of felling.

Quite often some, though not all, of the original outer rings are missing on a timber. The outer rings on an oak, called sapwood rings, are usually lighter than the inner rings, the heartwood, and so are relatively easy to identify. For example, sapwood can be seen in the corner of the rafter and at the outer end of the core in Figure A2, both indicated by arrows. More importantly for dendrochronology, the sapwood is relatively soft and so liable to insect attack and wear and tear. The builder, therefore, may remove some of the sapwood for precisely these reasons. Nevertheless, if at least some of the sapwood rings are left on a sample, we will know that not too many rings have been lost since felling so that the date of the last ring on the sample is only a few years before the date of the original last ring on the tree, and so to the date of felling.

Various estimates have been made and used for the average number of sapwood rings in mature oak trees (English Heritage 1998). A fairly conservative range is between 15 and 50 and that this holds for 95% of mature oaks. This means, of course, that in a small number of cases there could be fewer than 15 and more than 50 sapwood rings. For example, the core CRO-A06 has only 9 sapwood rings and some have obviously been lost over time – either they were removed originally by the carpenter and/or they rotted away in the building and/or they were lost in the coring. It is not known exactly how many sapwood rings are missing, but using the above range the Laboratory would estimate between a minimum of 6 (=15-9) and a maximum of 41 (=50-9). If the last ring of CRO-A06 has been dated to 1500, say, then the estimated felling-date range for the tree from which it came originally would be between 1506 and 1541. The Laboratory uses this estimate for sapwood in areas of England where it has no prior information. It also uses it when dealing with samples with very many rings, about 120 to the last heartwood ring. But in other areas of England where the Laboratory has accumulated a number of samples with complete sapwood, that is, no sapwood lost since felling, other estimates in place of the conservative range of 15 to 50 are used. In the East Midlands (Laxton *et al* 2001) and the east to the south down to Kent (Pearson 1995) where it has sampled extensively in the past, the Laboratory uses the shorter estimate of 15 to 35 sapwood rings in 95% of mature oaks growing in these parts. Since the sample CRO-A06 comes from a house in Cropwell Bishop in the East Midlands, a better estimate of sapwood rings lost since felling is between a minimum of 6 (=15-9) and 26 (=35-9) and the felling would be estimated to have taken place between 1506 and 1526, a shorter period than before. Oak boards quite often come from the Baltic region and in these cases the 95% confidence limits for sapwood are 9 to 36 (Howard *et al* 1992, 56).

Even more precise estimates of the felling date and range can often be obtained using knowledge of a particular case and information gathered at the time of sampling. For example, at the time of sampling the dendrochronologist may have noted that the timber from which the core of Figure A2 was taken still had complete sapwood but that some of the soft sapwood rings were lost in coring. By measuring into the timber the depth of sapwood lost, say 20mm, a reasonable estimate can be made of the number of sapwood rings lost, say 12 to 15 rings in this case. By adding on 12 to 15 years to the date of the last ring on the sample a good tight estimate for the range of the felling date can be obtained, which is often better than the 15 to 35 years later we would have estimated without this observation. In the example, the felling is now estimated to have taken place between AD 1512 and 1515, which is much more precise than without this extra information.

Even if all the sapwood rings are missing on a sample, but none of the heartwood rings are, then an estimate of the felling-date range is possible by adding on the full compliment of, say, 15 to 35 years to the date of the last heartwood ring (called the heartwood/ sapwood boundary or transition ring and denoted H/S). Fortunately it is often easy for a trained dendrochronologist to identify this boundary on a timber. If a timber does not have its heartwood/sapwood boundary, then only a *post quem* date for felling is possible.

5. Estimating the Date of Construction. There is a considerable body of evidence collected by dendrochronologists over the years that oak timbers used in buildings were not seasoned in medieval or early modern times (English Heritage 1998; Miles 1997, 50–5). Hence, provided that all the samples in a building have estimated felling-date ranges broadly in agreement with each other, so that they appear to have been felled as a group, then this should give an accurate estimate of the period when the structure was built, or soon after (Laxton *et al* 2001, fig 8; 34–5, where 'associated groups of fellings' are discussed in detail). However, if there is any evidence of storage before use, or if there is evidence the oak came from abroad (eg Baltic boards), then some allowance has to be made for this.

6. Master Chronological Sequences. Ultimately, to date a sequence of ring widths, or a site sequence, we need a master sequence of dated ring widths with which to cross-match it, a Master Chronology. To construct such a sequence we have to start with a sequence of widths whose dates are known and this means beginning with a sequence from an oak tree whose date of felling is known. In Figure A6 such a sequence is SHE-T, which came from a tree in Sherwood Forest which was blown down in a recent gale. After this other sequences which cross-match with it are added and gradually the sequence is 'pushed back in time' as far as the age of samples will allow. This process is illustrated in Figure A6. We have a master chronological sequence of widths for Nottinghamshire and East Midlands oak for each year from AD 882 to 1981. It is described in great detail in Laxton and Litton (1988), but the components it contains are shown here in the form of a bar diagram. As can be seen, it is well replicated in that for each year in this period there are several sample sequences having widths for that year. The master is the average of these. This master can now be used to date oak from this area and from the surrounding areas where the climate is very similar to that in the East Midlands. The Laboratory has also constructed a master for Kent (Laxton and Litton 1989). The method the Laboratory uses to construct a master sequence, such as the East Midlands and Kent, is completely objective and uses the Litton-Zainodin grouping procedure (Laxton *et al* 1988). Other laboratories and individuals have constructed masters for other areas and have made them available. As well as these masters, local (dated) site chronologies can be used to date other buildings from nearby. The Laboratory has hundreds of these site sequences from many parts of England and Wales covering many short periods.

7. Ring-Width Indices. Tree-ring dating can be done by cross-matching the ring widths themselves, as described above. However, it is advantageous to modify the widths first. Because different trees grow at different rates and because a young oak grows in a different way from an older oak, irrespective of the climate, the widths are first standardized before any matching between them is attempted. These standard widths are known as ring-width indices and were first used in dendrochronology by Baillie and Pilcher (1973). The exact form they take is explained in this paper and in the appendix of Laxton and Litton (1988) and is illustrated in the graphs in Figure A7. Here ring-widths are plotted vertically, one for each year of growth. In the upper sequence of (a), the generally large early growth after 1810 is very apparent as is the smaller later growth from about 1900 onwards when the tree is maturing. A similar phenomenon can be observed in the lower sequence of (a) starting in 1835. In both the widths are also changing rapidly from year to year. The peaks are the wide rings and the troughs are the narrow rings corresponding to good and poor growing seasons, respectively. The two corresponding sequence of Baillie-Pilcher indices are plotted in (b) where the differences in the immature and mature growths have been removed and only the rapidly changing peaks and troughs remain, that are associated with the common climatic signal. This makes cross-matching easier.

*t*-value/offset Matrix

| | C45 | C08 | C05 | C04 |
|---|---|---|---|---|
| C45 | | +20 | +37 | +47 |
| C08 | 5.6 | | +17 | +27 |
| C05 | 5.2 | 10.4 | | +10 |
| C04 | 5.9 | 3.7 | 5.1 | |

Bar Diagram

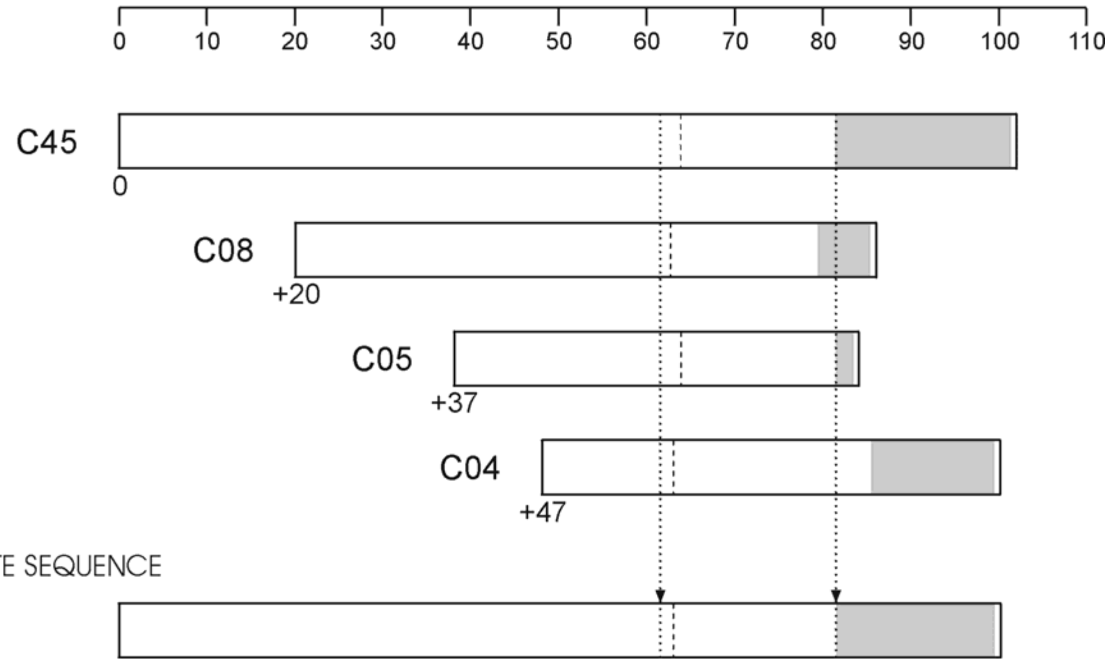



*Figure A5: Cross-matching of four sequences from a Lincoln Cathedral roof and the formation of a site sequence from them*

The bar diagram represents these sequences without the rings themselves. The length of the bar is proportional to the number of rings in the sequence. Here the four sequences are set at relative positions (offsets) to each other at which they have maximum correlation as measured by the *t*-values. The *t*-value/offset matrix contains the maximum *t*-values below the diagonal and the offsets above it. Thus, the maximum *t*-value between C08 and C45 occurs at the offset of +20 rings and the *t*-value is then 5.6. The site sequence is composed of the average of the corresponding widths, as illustrated with one width.

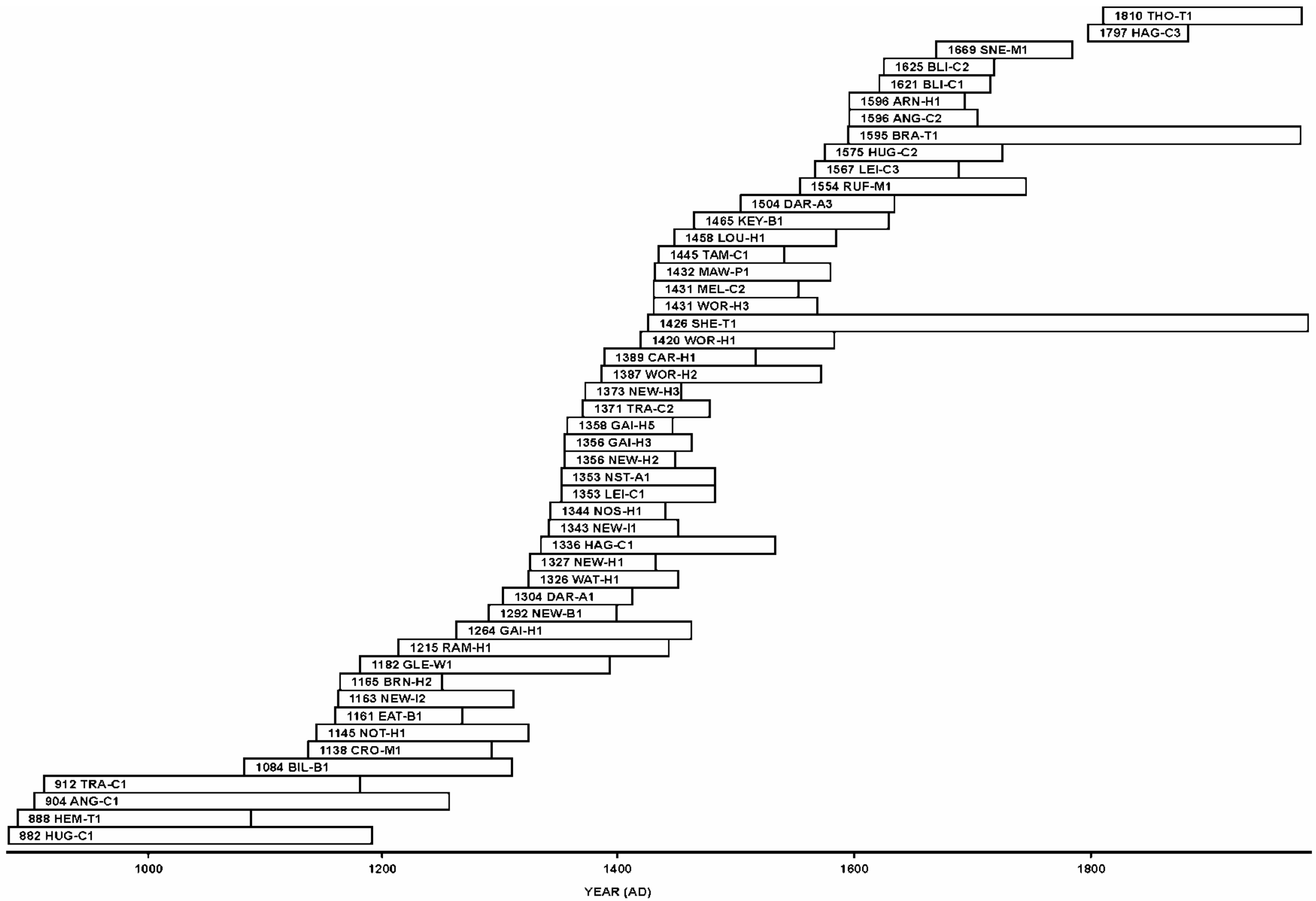
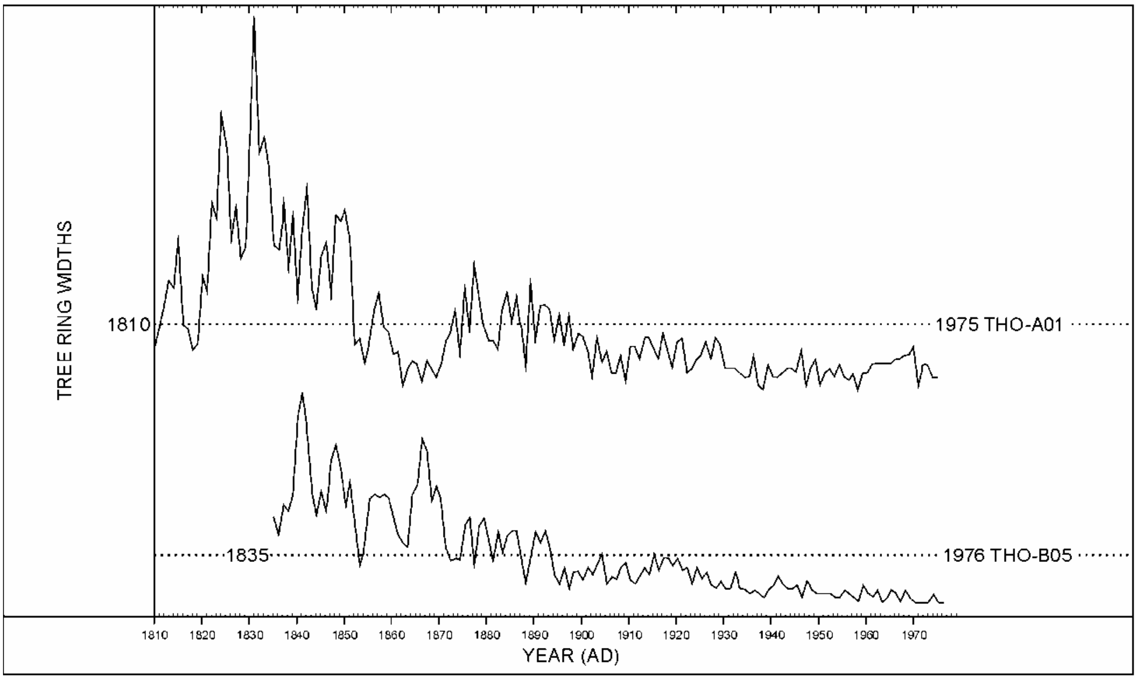



*Figure A6: Bar diagram showing the relative positions and dates of the first rings of the component site sequences in the East Midlands Master Dendrochronological Sequence, EM08/87*

(a)




(b)

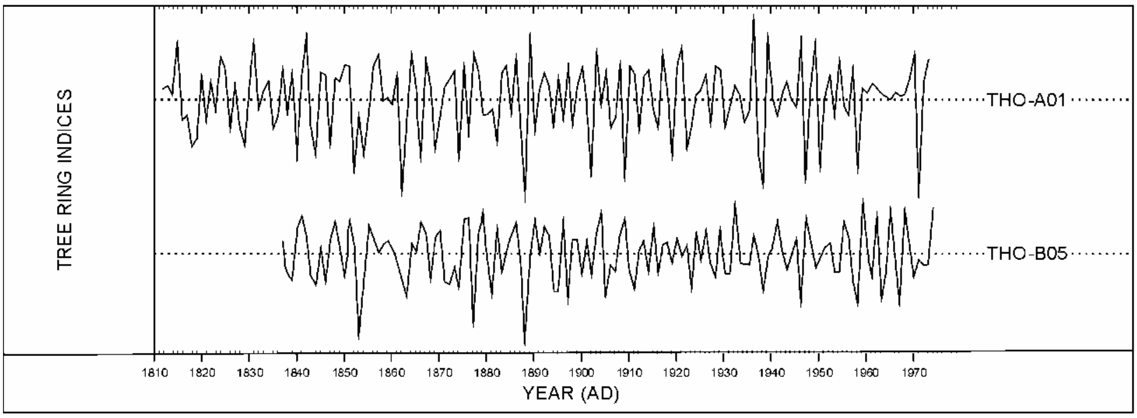



*Figure A7 (a): The raw ring-widths of two samples, THO-A01 and THO-B05, whose felling dates are known*

Here the ring widths are plotted vertically, one for each year, so that peaks represent wide rings and troughs narrow ones. Notice the growth-trends in each; on average the earlier rings of the young tree are wider than the later ones of the older tree in both sequences

*Figure A7 (b): The Baillie-Pilcher indices of the above widths*

The growth trends have been removed completely

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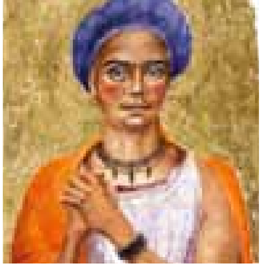


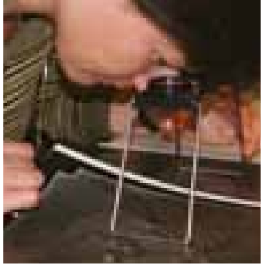


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